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THESIS

WIRELESS NETWORKS FOR BEAMFORMING IN DISTRIBUTED PHASED ARRAY RADAR

by

Jose Saul Gomez Noris

September 2007

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This thesis research addressed the wireless networking of the full-scale radar system. An analysis of the various existing and newly developed wireless technologies and guided transmission media was conducted to determine a baseline approach for the full system implementation.

A two-element array demonstrator was wirelessly networked and tested to allow wireless communication between the central beamformer and controller and the T/R modules. Control and monitoring software was developed in LabVIEW that allows simultaneous transmission and reception in both T/R modules.

Finally, a number of tests and measurements were conducted to validate the operation of the two-element array demonstrator while transmitting the control data wirelessly.

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**WIRELESS NETWORKS FOR BEAMFORMING
IN DISTRIBUTED PHASED ARRAY RADAR**

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Submitted in partial fulfillment of the
requirements for the degree of

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iii

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ABSTRACT

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TABLE OF CONTENTS

LIST OF FIGURES

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LIST OF TABLES

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I. INTRODUCTION

In recent years, there has been an accelerated proliferation of ballistic missile technology. As a result, missiles are more sophisticated, more difficult to counter, and more widely distributed. There are also many countries working to develop and improve biological, chemical and nuclear weapons that can be used along with ballistic missiles and represent a big threat against the security and peace of the world.

It is believed that North Korea has more than 800 ballistic missiles [1]; among them they have developed an Intercontinental (long range) Ballistic Missile, the Taepodong-2, with the potential capability to reach Alaska, Hawaii, and some parts on the west coast of the United States directly from East Asia.

The U.S. Department of Defense (DoD) has among its priorities the establishment of a Ballistic Missile Defense System to protect the United States of America, and its allies.

A. BACKGROUND

More than 20 years ago, President Ronald Reagan sent a challenge to develop anti-ballistic missile technology to defend and protect the United States, its territories, forces, and its allies against any ballistic missile attack. Since then, the Department of Defense (DoD) and the Missile Defense Agency (MDA) are working to develop a layered defense system with the intended capability of detection, interception and, destruction of short, intermediate, and long range missiles.

Intercontinental Ballistic Missiles (ICBMs) are typically designed for nuclear weapons delivery. They are long range missiles with range and speed greater than other ballistic missiles, these characteristics make them hard targets to detect and intercept, allowing just a short time to react and defend against them. Modern ICBMs can also carry multiple independent nuclear warheads, which allow a single missile to hit multiple targets simultaneously.

It is possible to identify three different phases during the flight cycle of a ballistic missile: the boost phase, midcourse phase, and the reentry phase. The Missile Defense Agency, in order to get a better probability of success, is taking into account each of these three phases while developing a layered integrated system to counter ballistic missiles. This system is known as Ballistic Missile Defense System (BMDS).

The BMDS has, so far, the capability to provide defense against short and intermediate range ballistic missiles. The capability to provide defense against Intercontinental Ballistic Missiles is still under development.

As part of this layered integrated defense forming the BMDS, there are several sensors and weapons. Among the sensors, there are Early Warning Radars, Midcourse X-Band Radar, Sea Based Radars, and Space Tracking and Surveillance Sensors forming a network of satellites. Among the weapons, there exists the Aegis Ballistic Missile Defense, Ground Base Interceptors, Kinetic Energy Interceptors, and the Patriot Advanced Capability-3, all of them with the mission of providing defense against missiles of all ranges in all phases of flight, as depicted in Figure 1.

Figure 1.   Integrated Ballistic Missile Defense System (From [2]).

In charge of the coordination and integration of all these layers of sensors and weapons, there is an advanced command, control, battle management, and communications network.

B. THESIS MOTIVATION

1. Sea-Based Systems

Sea-based BMDS have the potential strength to conduct operations from tactical locations at sea, that are not accessible by ground based systems, and they can also rapidly change their position to a new location as needed. However, while operating at a forward position, they are also more vulnerable to an attack.

The U.S. DoD has an ongoing program to develop a new generation of Multi-mission Advanced Destroyers, called the DD(X) Multi-mission Surface Combatant program. Developed under the DD(X) destroyer program, multi-mission surface combatants are tailored for littoral dominance and land attack with the capability to defeat current and projected threats.

Zumwalt class (DD(X)) destroyers will be designed with stealth technologies to reduce its acoustic, magnetic, infrared, radar, and visual signatures. An Engineering Development Model has been completed and includes an advanced gun system, integrated power system, composite deckhouse, peripheral vertical launch system, integrated sonar system, and dual band radar suite [3]. Figure 2 shows the Zumwalt class destroyer concept.

Phased array radars are becoming the most popular choice for modern communication and radar systems. The dual band radar suite is planned to consist of radar for Volume and Horizon search. The Volume Search Radar (VSR) working on L-band is integrated with the AN/SPY-3 Multi Function Radar (MFR), which is an X-band active phased array radar designed to detect low observable anti ship cruise missiles and support fire control illumination.
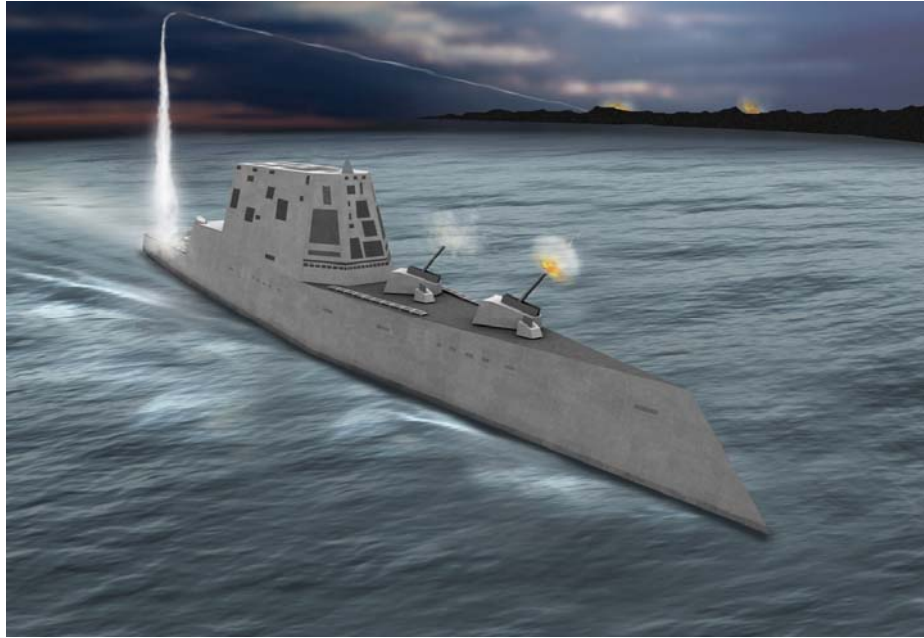
Figure 2.   Zumwalt Class Destroyer concept (From [4]).

Phased array radars with long range Early Warning capability are too bulky and heavy for shipboard installation, and the dual band radar suite planned for the DD(X) program is intended to track and intercept short and intermediate ballistic missiles, but has limitations in tracking Intercontinental Ballistic Missiles for a variety of reasons as addressed in [9]. A major problem is the amount of time required searching, which consumes much of the radar's resources. A more efficient approach is to use a secondary radar for search, which frees up the primary radar for its high priority functions. Furthermore, the secondary radar's performance can be optimized for the long range detection task.

There is an ongoing project at the Naval Postgraduate School sponsored by the Office of Naval Research (ONR) which its primary function is ship-based exo-atmospheric surveillance, tracking, and preliminary discrimination for BMD. The goal is to improve radar performance and detection range to detect targets over 1000 km away by designing and developing a ship based digital phased array radar that meets the Ballistic Missile Defense Program needs.

The array architecture applies three relatively new concepts:

- **Opportunistic**. The opportunistic array concept is based on placing the antenna elements at available open areas over the entire length of the ship. There is no need for a dedicated large area on the surface of the ship to place the radar antenna.

- **Aperstructure**. Based on the aperstructure concept, the antenna is integrated into the structure and almost the full length of the ship becomes the aperture of the phased array radar. This concept aims to provide the advantage of a very high angular resolution.

- **Wirelessly Networked Digital Architecture**. This concept aims to implement stand-alone modules at each antenna element, wirelessly networked to a central processor with the power supply as the only wired connection. The wireless beamforming concept is illustrated in Figure 3.
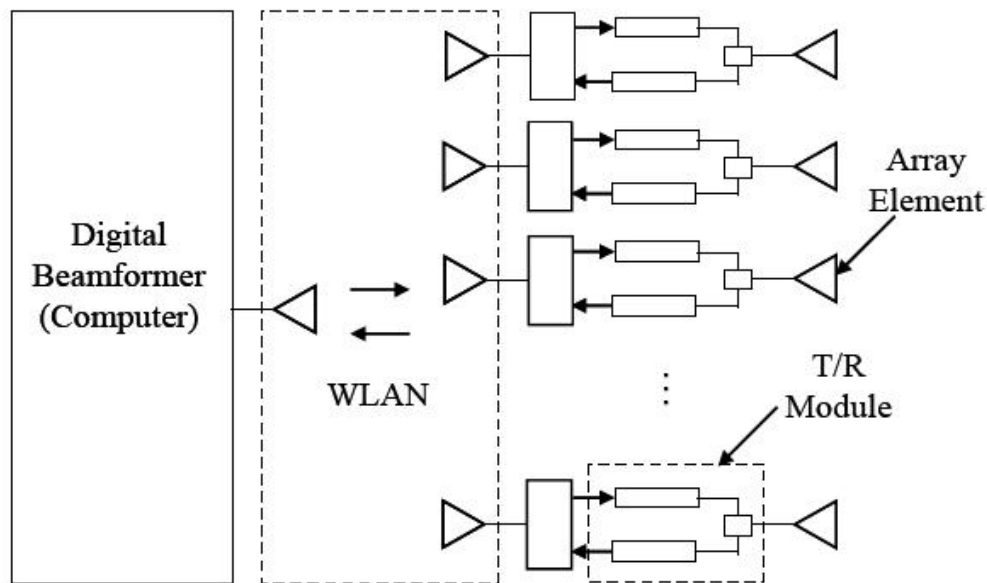
Figure 3.   Wirelessly networked phased array architecture (From [5]).

Among the advantages that these three new concepts introduce are the following: survivability, enhanced stealth, flexibility, multifunction, and operational availability.

The increased survivability is achieved given that every antenna element is independent of each other, so if an antenna element fails the complete network can still develop its required functions. The enhanced stealth capability is achieved by integrating the antenna elements into the ship's structure, with an inherent reduction of the Radar Cross Section (RCS) and visual signature. The wireless nature of the system allows the flexibility to easily add, remove, or relocate antenna elements as needed, as well as upgrade or reconfigure the software. The wirelessly networked digital architecture allows also the possibility to develop multiple secondary functions like communications, direction finding and Electronic Attack, where a sufficient amount of electromagnetic energy is used to disrupt enemy sensors. Finally, there is also an improvement in the operational availability in an opportunistic array compared with conventional radars, given that the antenna elements are dispersed all around the ship, ensuring that radar operations will continue even if a number of elements are disabled for any given reason. Furthermore, damaged antenna elements can be easily replaced given their modularity and accessibility.

There are several technical challenges in the realization of a wirelessly networked aperstructure array. One is the synchronization of elements to a common phase and frequency reference. Another is the wireless transfer of vast amounts of data between the elements and central processor in real time. The wireless network is the primary focus of this thesis.

C.   PREVIOUS WORK

The development and demonstration of some of the concepts included in the Wirelessly Networked Digital Array project have been addressed in past research as follows.

- In [6], Esswein applied the concepts of Generic Algorithms and the Method of Moments while designing and testing a model of a transmit phased array antenna with 24 elements using commercial-of-the-shelf (COTS) modulator boards, AD8346 from Analog Devices.

- The complementary receive array model was developed and examined using commercial demodulator boards (AD8347) from Analog Devices, having as a conclusion that the demodulators are suitable for the receive application [7].

- In [8], Ong developed a transmit setup to test and demonstrate that a bandpass filter is needed to suppress the image sideband signal generated by the modulator board (AD8346) when used together with the Direct Digital Synthesizer (DDS) evaluation board AD9854.

- The research was continued by analyzing different methods to synchronize DDS boards (AD9854). The generation of different waveforms using a DDS was studied as well [9].

- The opportunistic array concept was investigated in [10] to demonstrate that detection ranges over 1000 km are achievable by using distributed array radar with at least 400 elements. The design of a broad-band U-slot microstrip patch antenna with the capability to operate in the VHF/UHF frequency band was also developed.

- In [11], Yong demonstrated that the wireless transmission of the Local Oscillator (LO) signal is possible, by wirelessly transmitting the LO signal to two modulator boards and testing the amplitude and phase characteristics. He also analyzed the digitization of data and control signals among the central controller and the Transmit/Receive (T/R) modules.

- The problems of integration and phase synchronization of array elements was addressed in [12] and was demonstrated using a simple

7

synchronization circuit. Also, results from analysis and simulation concluded that it is not necessary to use a position location scheme to correct for dynamic effects of hull deflection for an array operating in the VHF/UHF frequency band. A proposed design model for a demonstration T/R module was also presented.

- The development of a demonstration T/R module, along with the characterization and evaluation of its component devices was presented in [13]. Analysis and simulation were conducted to determine the expected antenna beam patterns from an eight-element array demonstrator.

- In [14], Yeo developed a two-element array test bench using Compact Reconfigurable Input and Output (cRIO) and Field Programmable Gate Array (FPGA) modules from National Instruments, to demonstrate the functionalities of transmission and reception of the T/R modules. Several measurements were taken and presented in order to demonstrate that no significant interference exists between the modulator and demodulator boards inside the T/R module.

This research builds on the results of Yeo [14] by demonstrating wireless data transfer between the elements of the two-element array and the master controller.

D.   OBJECTIVES

The first objective is to perform a trade off study of the various existing and newly developed wireless technologies, and configurations that could be implemented in a Wirelessly Networked Distributed Phased Array Radar. This includes the possible implementation of optical fiber links in combination with wireless networks to meet the high data rates required for the full-scale system.

The system analysis and hardware implementation of wireless networking for the two element array demonstrator described in [14] is also addressed.

The development of the software to test and demonstrate the functionalities of wireless transmission and reception of the T/R modules is conducted using LabVIEW.

Finally, measurements are necessary to characterize the performance of the wireless network between the T/R modules. This includes the measurement of system latency and effective data rate.

E. THESIS ORGANIZATION

Chapter II describes the system architecture of the Wireless Networked Aperstructure Digital Phased Array Radar concept, its main components, and characteristics, as well as relevant functionalities to be achieved.

Chapter III addresses the challenge of the wireless communication between the central beamformer and controller and the T/R modules in a Wireless Networked Aperstructure Digital Phased Array Radar. A study of the characteristics of the transmission medium necessary to implement a full-scale system is also presented.

In Chapter IV the hardware and software development for the wireless networking of a two-element array demonstration is described.

Chapter V presents the different measurements conducted to test the performance of the two-element array demonstrator while transmitting information data wirelessly with a wired LO signal.

Finally, in Chapter VI the conclusions of this research are presented along with some recommendations for future work.

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II. SYSTEM ARCHITECTURE

This chapter points out the current state of an ongoing project at the Naval Postgraduate School related with the Wirelessly Networked Aperstructure Digital Phased Array Radar, as well as the future goals expected to be achieved.

A. BACKGROUND

The name phased array describes an antenna made up of a number of individual radiating elements forming a directive antenna. By controlling the magnitude and phase of the current at each of these elements, it is possible to determine the antenna's radiation pattern. This property gives the capability and advantage of electronically steering the beam's angle of a large phased array antenna by changing only the phase at each radiating element; therefore there is no need for mechanically rotating a big and bulky antenna.

Some of the advantages of electronically steerable phased arrays [15] are the following:

- Allow multifunction radar operation.

- Reduce the radar cross section if properly design.

- Agile and rapid beam-steering.

- Allow multiple target tracking.

- Potential for large peak and large average powers.

- Easy control of the aperture illumination given the many antenna elements available.

On the other hand, the main disadvantages of phased array radars are that can be of high cost and high complexity.

The idea behind the Wirelessly Networked Aperstructure Digital Phased Array Radar (WNADPAR) concept is to develop ship based phased array radar for BMD purposes, with the radiating elements distributed all over available areas on the surface of the ship to improve the radar characteristics of detection range and form narrow beams.

Figure 4 depicts a DDG-1000 class ship model with 1,200 T/R modules randomly distributed on its superstructure and a polar plot of relative power pattern for broadside scan at 10° elevation.
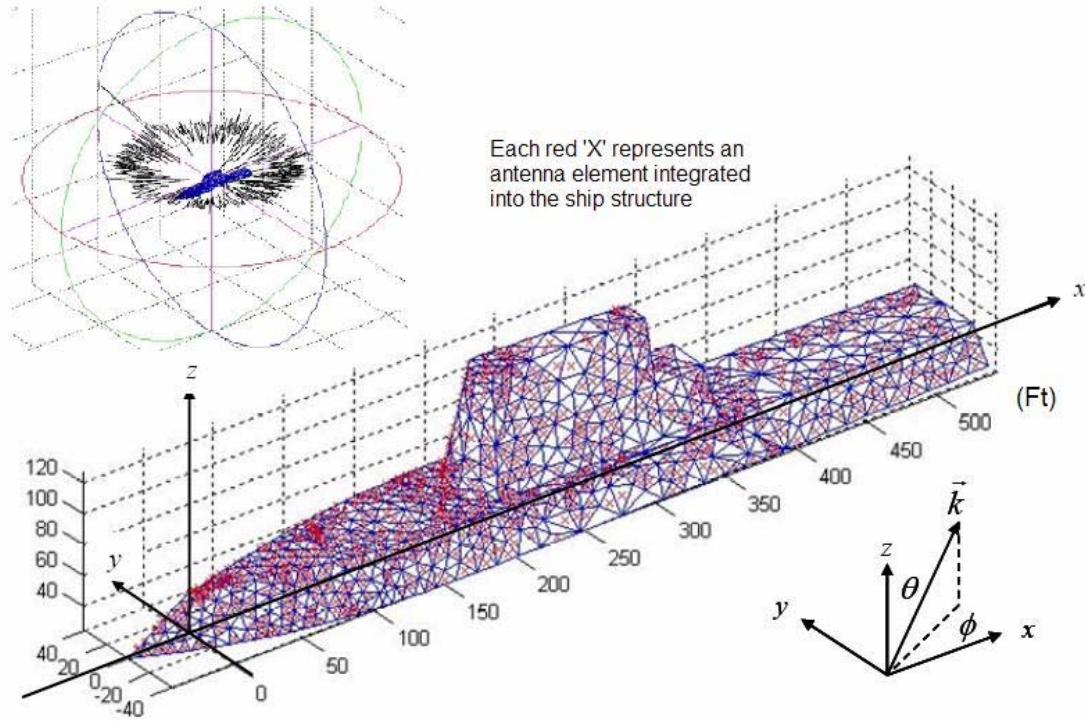
Figure 4.   Polar plot of relative power pattern and DDG-1000 class ship model with 1200 randomly distributed array elements (After [5]).

In order to achieve a long range detection capability, the radar's operating frequency is set at 300 MHz in the upper VHF or lower UHF band, to reduce propagation losses due to rain and atmospheric attenuation; sea and ground clutter are also minimal at this frequency. High angular resolution capability is achieved by utilizing the entire ship's structure as an aperture. Angular resolution is proportional to the antenna beamwidth, determined in degrees approximately by

12

$$\theta_B = \frac{\lambda}{D} \cdot \left(\frac{180}{\pi} \right) \tag{1}$$

where λ is the radar wavelength equal to 1 meter for an operating frequency of 300 MHz, and D is the size of the aperture. The DDG-1000 class ship is approximately 183 meters long and has a beam of 25 meters [16]; therefore, by using the entire length of the ship as the aperture, the phased array radar can achieve an angular azimuth resolution of about 0.31 degrees.

B.   SYSTEM OVERVIEW

The WNADPAR consists basically of a central digital beamformer with the function to collect and distribute information signals to and from all the elements forming the phased array. Each element has the capability to transmit and receive radar signals, with its T/R module. This network architecture implies the necessities and challenges of phase and time synchronization between the elements and the central controller, very high processing speed, and high data rate at the network links to allow real-time operation.

In the full-scale model, with the phased array radar integrated on the ship superstructure, the digital beamformer and controller must be placed below deck for protection and safety. All of the hundreds or even thousands of self-standing T/R modules can be randomly distributed on available areas over the ship's hull and superstructure.

The basic operational concept of the WNADPAR is the following. During the transmission phase, the central digital beamformer and controller generates the required signals of the local oscillator, phase synchronization, beam control data, and radar waveform parameters, and sends them wirelessly to all the T/R modules. During the reception phase, each antenna element sends the baseband target echo data back to the controller for signal processing. Once the controller has an echo data from each one of the active T/R modules, it can compute the target's position. Figure 5 depicts a

representation of the wireless beamforming architecture onboard a ship, where only one array element with its T/R module is shown for simplicity.
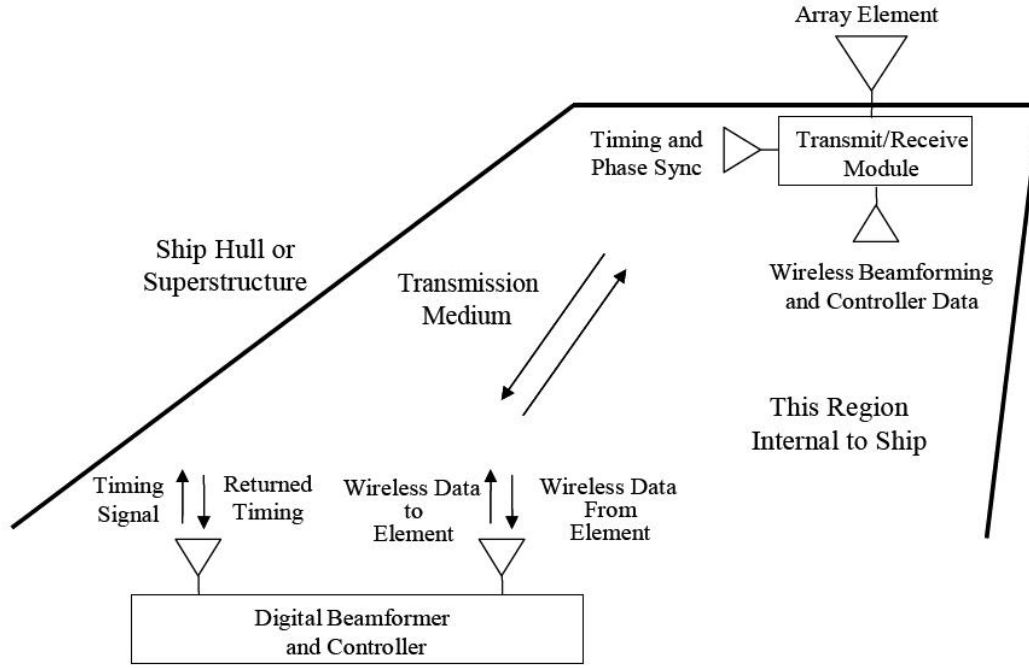
Figure 5.　　Wireless beamforming architecture (From [5]).

In order to achieve coherent operation of the radar system, every array element must be synchronized in phase and time. Phase synchronization means that the local oscillator signal at every array element must have the same phase both on transmit and receive. These LO signal phases have to be adjusted based on the propagation channel characteristics and distances from each T/R module to the central controller where the LO source resides. Time synchronization is needed to coordinate the transmission and reception periods at each T/R module.

Time and phase synchronization of all T/R modules increases the signal-to-noise ratio (SNR) and average power by ensuring that the transmitted signal converges coherently on the target.

A typical module architecture is shown in Figure 6. In the transmit mode, after receiving the information data sent by the central beamformer and controller (comprised

14

of the beam control data and radar waveform parameters along with the synchronization and LO signals) the module's Direct Digital Synthesizer (DDS) generates the digital baseband signal. The modulator then introduces the needed phase translation (modulation) to the carrier signal, and it is converted to analog with the digital to analog converter (D/A). This modulated carrier signal is amplified with a Power Amplifier (PA), passed through the circulator, and sent to the antenna for transmission. If the number of synchronized and coordinated T/R modules is large enough, the total output power can provide the desired long range detection capability. The total transmit power is N times the power of a single element when N equal power elements transmit coherently. Furthermore the collective gain of the array is NG_o where G_o is the gain of a single element [14].
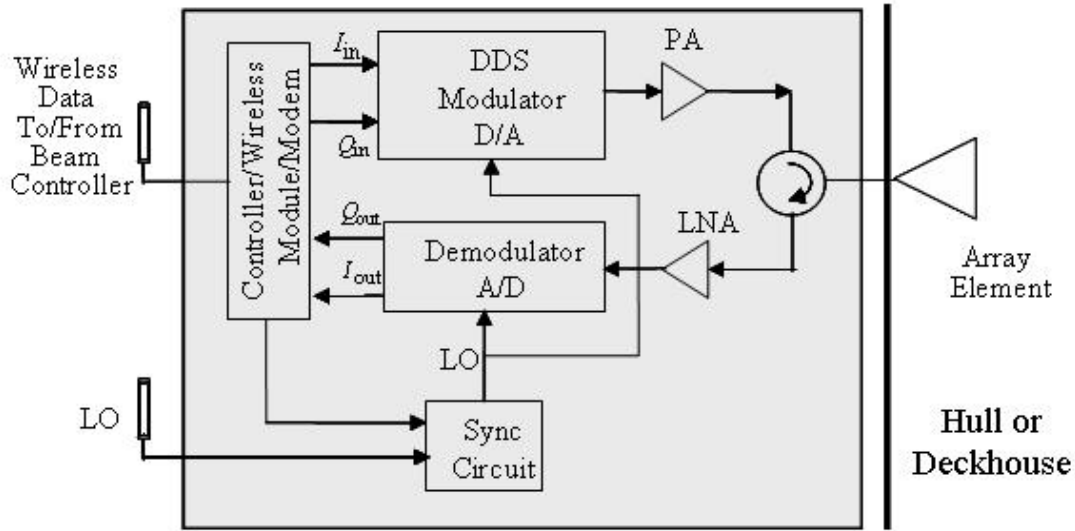
Figure 6.   Detailed architecture of a T/R module (From [17]).

On the receive side, the radio frequency signal goes from the circulator to the Low Noise Amplifier (LNA), and then the demodulator recovers the baseband signal from the target's echo. It is converted back to digital form with the analog to digital converter (A/D), and the resulting data (I and Q signals) are sent to the central beamformer and controller for signal processing.

1.   Synchronization and Timing

Synchronization is an essential part of the radar process in order to achieve coherent operation. In [12], a brute force synchronization technique was proposed as the easiest technique to implement, but not the most efficient. Its implementation requires some additional hardware in every T/R module, as denoted by the "Sync Circuit" box in Figure 6.

Figure 7 shows a detailed diagram of the synchronization circuit. To synchronize element *n*, its operation consists of using a reference signal from a reference T/R module and subtracting it from the phase of T/R module number *n*. If the difference is not zero, a phase shift needs to be introduced in the element's signal and compared again against the reference signal. This process should continue until the difference between the reference phase and the element phase is zero, then the synchronization is complete and the system can move on to the next element to be synchronized.
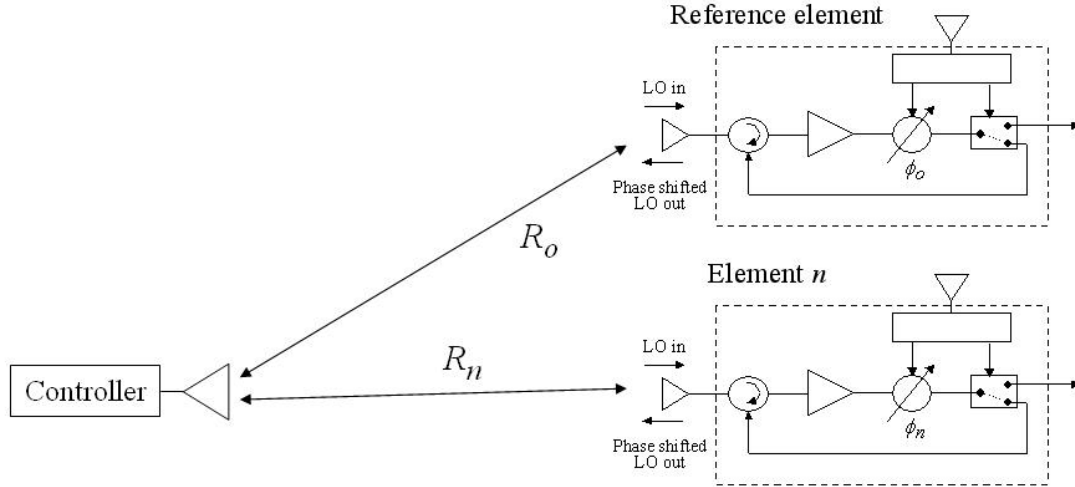
Figure 7.   Phase synchronization block (From [17]).

With respect to the element geolocation, the central controller needs to know the exact position of each element in order to compute accurate phase information for beam scanning based on the location of the T/R module. The element position needs to be established within a fraction of wavelength to compensate for phase errors. It was

16

demonstrated by simulation [12] that a position location scheme to correct for dynamic effects of hull deflection is not absolutely necessary given the radar's operating frequency (300 MHz). The hull deformation is small enough compared to the wavelength so that it can be ignored.

C. SUMMARY

This chapter described the system architecture of the Wirelessly Networked Aperstructure Digital Phased Array Radar. A detailed description of the concepts behind the WNADPAR and the functions of the main components in each array element were also presented.

The next chapter discusses the details of the wireless data communication between the central beamformer and controller and the T/R modules, as well as the transmission medium necessary to implement a full-scale system.

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III. DATA TRANSFER AND COMMUNICATION BETWEEN THE ELEMENTS AND CONTROLLER

This chapter addresses the challenges presented by the wireless communication aspect of the Wirelessly Networked Aperstructure Digital Phase Array Radar.

Conventional arrays in many radar and communication applications use microwave circuits as beamformers. Traditionally, the elements of an array are connected by a system of microwave transmission lines and power dividers. These microwave circuit beamformers have the disadvantages that make the array antenna large and heavy if a large number of elements are required. They tend to be narrow band, and can not be adjusted to change the beam sidelobe levels. Therefore, these beamformers would not be suitable for shipborne applications where elements are distributed over the entire ship.

On the other hand, the use of a wireless network as beamformer makes the system adaptable to the operational environment, survivable, and very flexible, by adding the capability to reconfigure and add or replace elements as needed.

The wireless network relies on the existence of a good quality propagation channel from the controller to all elements. Long range (entire ship length) wireless connectivity internal to the ship is a concern. Several options are discussed to reduce the problem. The four approaches are depicted in Figure 8.

- Incorporate relays between compartments.

- Use hardwire connections to the elements (optical or radio frequency, RF).

- Combine a small number of hardwire runs to remote parts of the ship with short range wireless links at each of the terminations.

- Employ a transmission system that is integrated into the ship structure.

Finally, the data rate required for the beamforming is estimated, and the data handling capabilities of various network configurations are examined.

19
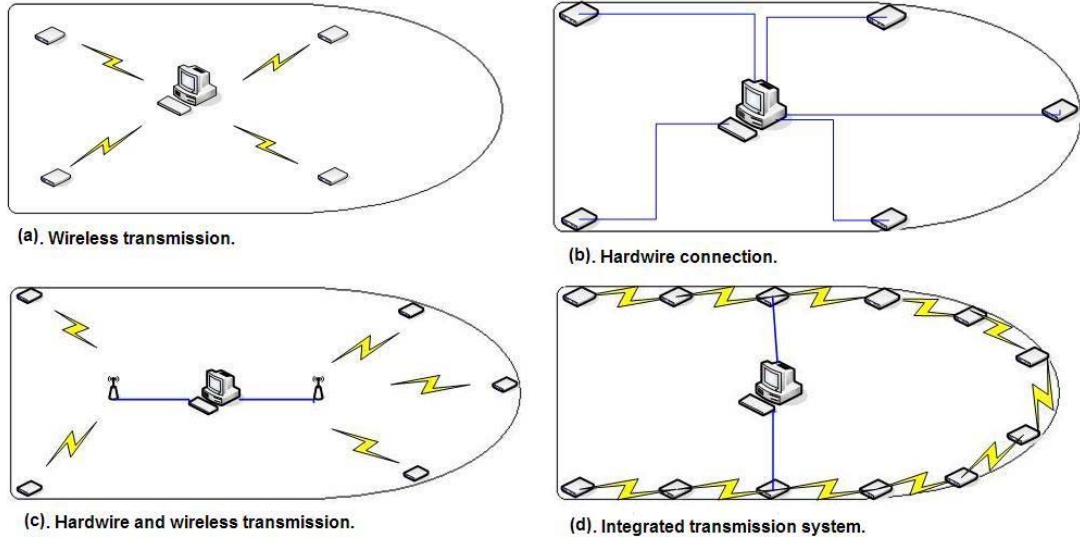
Figure 8.   Possible data network configurations.

A.   WIRELESS TRANSMISSION

The implementation of a full-scale WNADPAR requires about 1,200 antenna elements each transmitting an average power of 500 W, if a detection range of 2,000 km is desired [12]. The data rate requirement for every T/R module is dominated by the high resolution of the ADC at the receive channel, given that the data to be sent by the transmitter is really small in contrast. If a four-channel ADC is used, and each channel is sampled simultaneously at R_s samples per second, with a resolution in bits of N_b, the bit rate required per array element is

$$R_b = 4 \times N_b \times R_s \tag{2}$$

In the case of the two element array demonstrator shown in Figure 9, each T/R module has a four-channel ADC in the National Instruments module (NI-9215), each with a maximum sampling rate of 100 kS/s, and a resolution of 16 bits. Therefore, using Equation (2) the expected bit rate is 6.4 Mbps per array element.
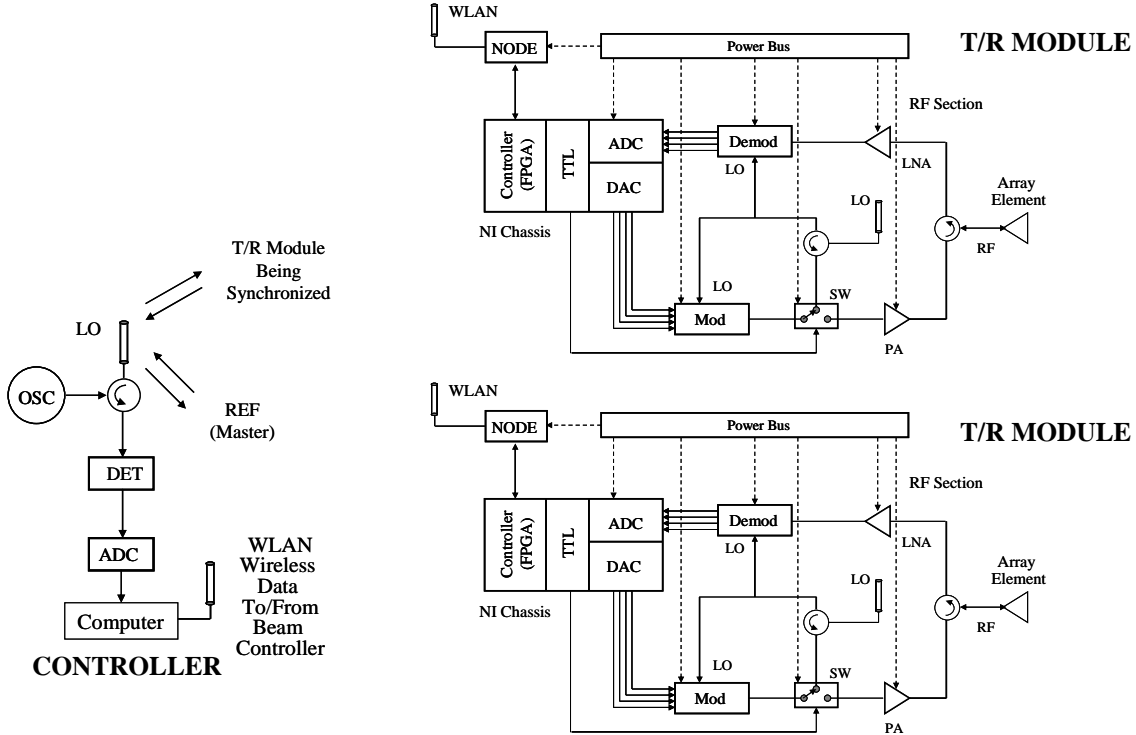
Figure 9.   Block diagram of a two-element array demonstrator (From [17]).

For an antenna array with N elements, the total bit rate required is 6.4N Mbps. If the WNADPAR has 1,200 antenna elements, the full wireless network needs to handle a total data rate of 7.68 Gbps. Implementation of the full scale system using commercial technologies depends basically on the development of wireless communication standards with the capability of gigabit transmission rates.

1.   Commercial Wireless Technologies

Wireless Local Area Networks (WLAN) transmit using radio frequencies, so they are regulated by the Federal Communications Commission (FCC), while the Institute of Electrical and Electronics Engineers (IEEE) defines the standards for how RF transmissions can be used to carry data. In the confines of the ship, the frequency spectrum usage need not adhere to the FCC's allocation, however if wireless networks onboard spread to other frequency bands then many other wireless systems may be negatively affected.

Wireless technology is being more widely used in many new applications. WLAN technology commonly includes the following standards: Wi-Fi (IEEE 802.11), Bluetooth, Ultra-Wide Band (UWB), and Wimax.

In recent years, Wi-Fi has become increasingly popular by enabling people to link computers to wireless LANs, either to give greater flexibility, to reduce costs by not having to install wired networks or just to access a computer network wirelessly in public areas. The most widely known standards under the IEEE 802.11 are [18]:

- 802.11a – Wireless network bearer operating in the 5 GHz ISM band with data rates up to 54 Mbps.

- 802.11b – Wireless network bearer operating in the 2.4 GHz ISM band with data rates up to 11 Mbps.

- 802.11g – Wireless network bearer operating in the 2.4 GHz ISM band with data rates up to 54 Mbps.

- 802.11n – Wireless network bearer operating in the 2.4 and 5 GHz ISM bands with data rates up to 200 Mbps.

All the 802.11 Wi-Fi standards operate within the Industrial, Scientific and Medical (ISM) frequency bands. These are shared by a variety of other users, but no license is required for operation within these frequencies. This makes them ideal for a general system for widespread use.

Each of the standards has different features and uses different modulation schemes such as Complimentary Code Keying (CCK), Direct-Sequence Spread Spectrum (DSSS), or Orthogonal Frequency Division Multiplexing (OFDM). The main characteristics of each standard are summarized in Table 1.

	802.11a	802.11b	802.11g	802.11n
Maximum data rate (Mbps)	54	11	54	200
Modulation	OFDM	CCK, OFDM	CCK, DSSS, OFDM	CCK, DSSS, OFDM
RF Band (GHz)	5	2.4	2.4	2.4, 5
Number of spatial streams	1	1	1	1, 2, 3, 4
Channel width (MHz)	20	20	20	20, 40

Table 1.   Summary of 802.11 Wi-Fi Standards.

The IEEE 802.11n standard promises higher speeds and longer ranges than earlier Wi-Fi versions. 802.11n uses multiple-input, multiple-output (MIMO) technology to improve its transmission speed and range, by taking advantage of the multiple paths between a transmitter and receiver. MIMO systems use multiple sending and receiving antennas, each transmit antenna sends different data streams simultaneously on the same frequency channel. Then MIMO relies on signals traveling on multiple paths between an array of transmit antennas and an array of receive antennas. Each path propagates an image of one transmitted signal (from one antenna) that differs in both amplitude and phase from the images following other paths. Each image arrives at one of the receive antennas at slightly different times, and the phase differences are used to differentiate between them [19]. By using multiple paths as additional data paths, rather than just redundant carriers of the original signal, increased bandwidth and transmission range are achieved.

Multipath occurs when transmitted signals bounce off objects and create reflected signals that take multiple paths to the receiver. MIMO technology takes advantage of these multiple paths to achieve higher data rates as illustrated in Figure 10.
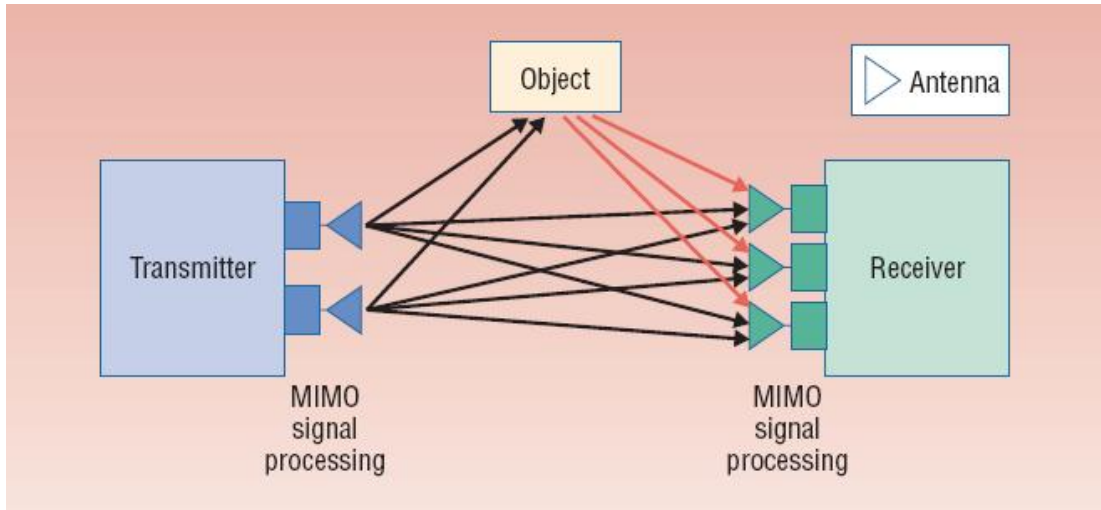
Figure 10.　　　Multiple-Input, Multiple-Output concept (From [20]).

Bluetooth is a wireless standard with the capacity to carry data at speeds up to 721 kbps in its basic form. It runs in the 2.4 GHz ISM band and employs frequency hopping techniques with the carrier modulated using Gaussian Frequency Shift Keying (GFSK). The data rates provided by Bluetooth are adequate for audio and most file transfer; however, they are insufficient for many other applications that require higher data rates.

UWB is known as the next generation of high speed wireless technology that occupies a very wide bandwidth and enables high data rates around 480 Mbps within ranges up to 10 meters. UWB transmission frequencies cross the boundaries of many licensed technologies, but interference is avoided with a very low power spectral density. The power limits on UWB are being strictly limited. The FCC has mandated that UWB radio transmission can legally operate in the range from 3.1 to 10.6 GHz, at a limited transmitted power of -41 dBm/MHz [21].

The IEEE 802.16 Wimax standard is a wireless data communication technology that specializes in point-to-multipoint broadband wireless access. This technology offers high-speed voice, video and data services for the "last mile", which is presently dominated by the cable and Digital Subscriber Line (DLS) technologies. The biggest

advantages of Wimax over wired technologies are its increased capacity and ease of deployment, and the biggest obstacles for its deployment are its cost and the overall performance of the system.

Initially, the 802.16a standard was developed and launched, but now it has been further refined and replaced by the 802.16d and 802.16e standards, currently available. Wimax uses as modulation scheme OFDM operating in different frequencies between 2 and 10 GHz. The frequencies commonly used are 3.5 and 5.8 GHz for 802.16d and 2.3, 2.5, and 3.5 GHz for 802.16e, but this may change based mainly in the country.

- 802.16d – Provides data rates up to 75 Mbps with a coverage distances up to 75 km.

- 802.16e – Provides data rates up to 15 Mbps with a coverage distances between 2 and 4 km.

Figure 11 depicts a summary of the different wireless technologies, with indication of their data rate and coverage range. It is shown that the highest data rate is achieved by UWB within a short range of less than 10 meters, followed by the 802.11n standard, with a maximum coverage range of about 100 meters.
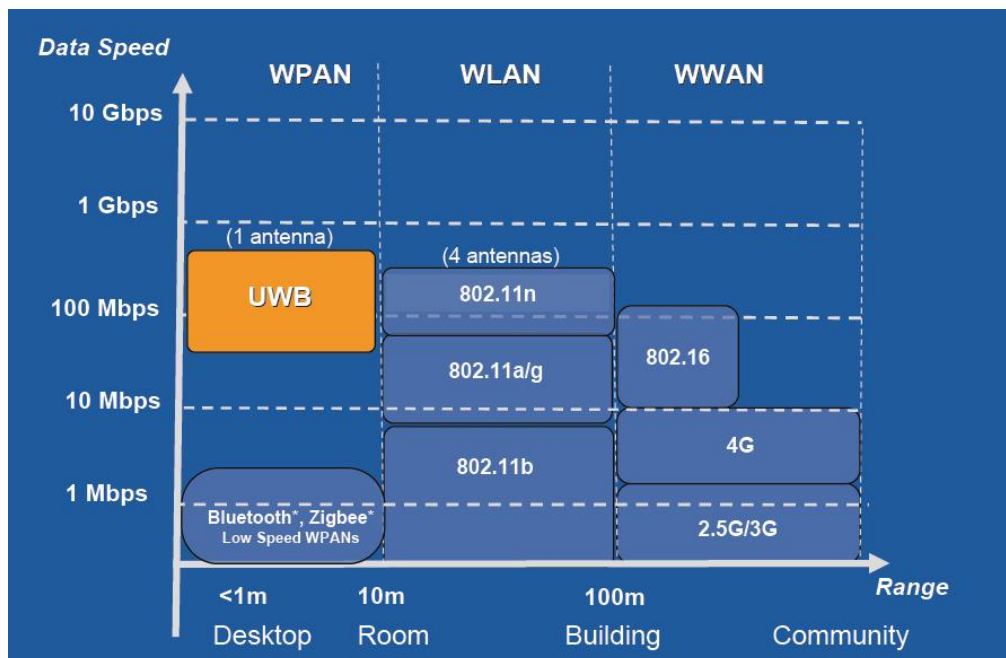
Figure 11.   Wireless technologies (After [22]).

B.   GUIDED TRANSMISSION MEDIA

Guided transmission media is an option for all or parts of the high speed network between the elements and controller. There are several factors like attenuation, operational frequency range, time delay, and whether repeaters are necessary that must be considered when planning a network. The use of a hardwired data network reduces the flexibility of the distributed array approach. It is more difficult to reconfigure the array when hardwire connections are involved. The wired network must also carry the synchronization and timing signals.

The most commonly used guided media for data transmission are twisted pair, coaxial cable, and optical fiber, however, it would be possible to incorporate an integrated transmission medium into the ship structure.

1.   Twisted Pair

A twisted pair is formed by two insulated cooper wires forming a single communication link. They are commonly arranged in a regular spiral pattern to decrease the crosstalk interference between adjacent pairs in a cable.

Twisted pair is the most common guided transmission media, mainly because of its low cost, but it is limited in distance, bandwidth, and data rate compared to other used guided transmission media.

2.   Coaxial Cable

Coaxial cable permits operation over a wider range of frequencies than twisted pair. It consists of a hollow outer cylindrical conductor that surrounds a single inner wire conductor held in place by either a solid dielectric material or regularly spaced insulating rings.

Coaxial cable is less susceptible to interference than twisted pair, but it has constraints on performance because of attenuation, thermal noise, and intermodulation noise.

3.   Optical Fiber

Optical fiber is a flexible medium, made of different glasses or plastics, capable of guiding an optical ray. Optical fiber is commonly used in long-distance telecommunications, but it is also very attractive for local area networking given its improvements in performance and decline in prices. The main advantages of optical fiber compared with twisted pair or coaxial cable are [23]:

- Lower attenuation. Attenuation on optical fiber is constant over a wide range, and it is significantly lower than that for coaxial cable or twisted pair.

- Greater data rate capacity. Data rates of hundreds of Gbps over tens of kilometers have been demonstrated.

- Smaller size and lighter weight. Optical fiber is thinner than twisted pair or coaxial cable; this also reduces the requirements of structural support.

- Electromagnetic isolation. Optical fiber systems are not vulnerable to interference given that they are not affected by external electromagnetic fields.

- Greater repeater spacing. This characteristic is mainly driven for the low attenuation. Fewer repeaters mean also lower cost and fewer sources of error.

The full-scale WNADPAR requires an estimated data rate of 7.68 Gbps with the central beamforming and controller. The 10-Gbps Ethernet standard defines 4 styles of optical transceivers [23].

- 10GBASE-S (short): Designed for 850 nm transmission on multimode fiber. This medium can achieve distances up to 300 m.

- 10GBASE-L (long): Designed for 1310 nm transmission on single-mode fiber. This medium can achieve distances up 10 km.

- 10GBASE-E (extended): Designed for 1550 nm transmission on single-mode fiber. This medium can achieve distances up 40 km.

- 10GBASE-LX4: Designed for 1310 nm transmission on single-mode or multimode fiber. This medium can achieve distances up to 10 km and uses wavelength division multiplexing to multiplex the bit stream across four light waves.

A summary of the transmission characteristics of each one of the different guided media is presented in Table 2.

	Frequency Range	Typical Attenuation	Typical Delay	Repeater Spacing
Twisted pair (with loading)	0 to 3.5 kHz	0.2 dB/km @ 1 kHz	50 µs/km	2 km
Twisted pair (multipair cables)	0 to 1 MHz	0.7 dB/km @ 1 kHz	5 µs/km	2 km
Coaxial cable	0 to 500 MHz	7 dB/km @ 10 MHz	4 µs/km	1 to 9 km
Optical fiber	186 to 370 THz	0.2 to 0.5 dB/km	5 µs/km	40 km

Table 2.   Transmission characteristics of guided media.

4.   Integrated Ship Transmission System

The wireless communication between the central controller and the T/R modules onboard a ship requires a quality that ensures minimal loss and proper propagation. Transmission between various points on the hull could be achieved by simply plugging the system into an integrated transmission medium, as shown in Figure 12.

Ideally, a transmission system would present the following characteristics: low noise, low loss, scalability, and easily implemented. To achieve such an integrated transmission system, three potential solutions are: (1) a parallel-plate waveguide sandwiching a dielectric medium, (2) a single-plate conducting plane with a thin film of dielectric, and (3) electromagnetic band gap (EBG) waveguide structure. The main characteristics of these three candidate solutions were investigated in [11] and [24].
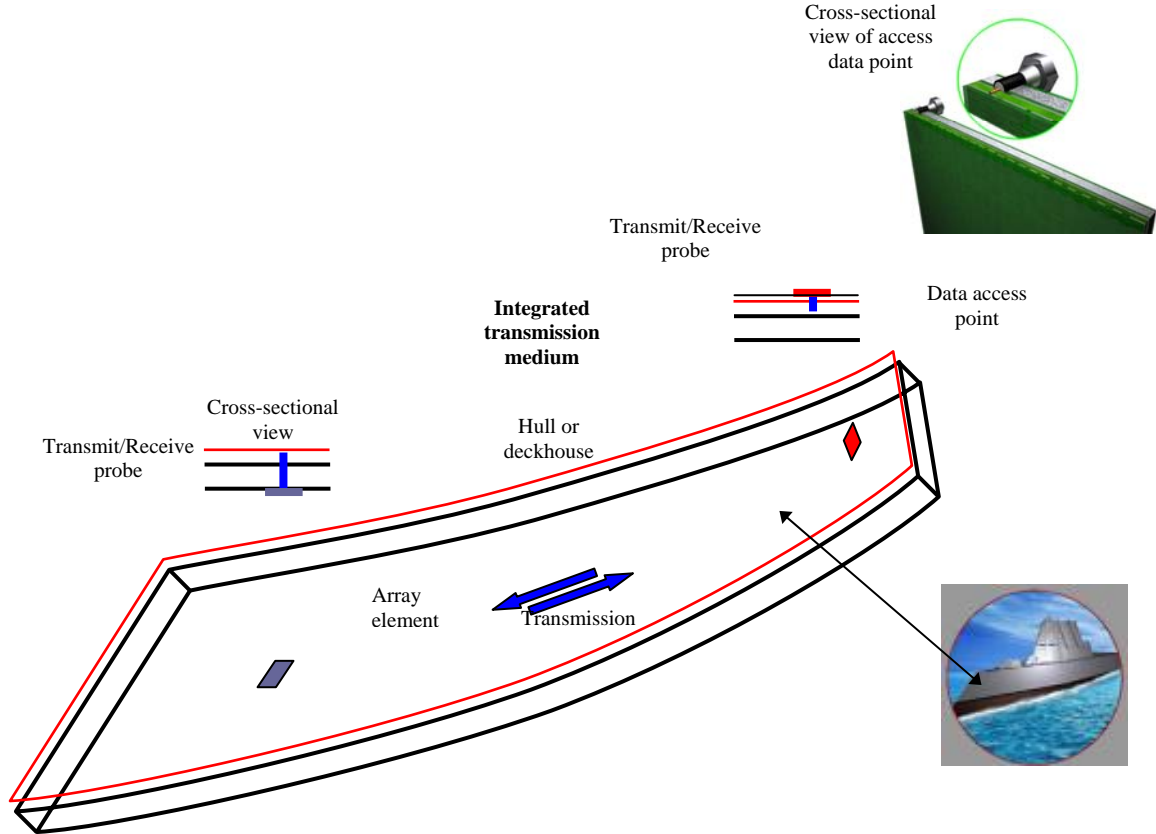
Figure 12.   Integrated transmission system (From [11]).

C.   WIRELESS COMMUNICATION IN A WNADPAR

Given the high data rate required for a full-scale WNADPAR comprised of 1,200 elements, using current technology there is no single and direct solution for the wireless beamforming issue using commercial devices. However, there are several solutions that can achieve the required data rates.

One possible solution to be considered consists in the implementation of multiple WLANs in parallel, using non-overlapping frequency bands. This approach implies the development and use of hardware working with operating frequencies out of the ISM bands and regulations established by the FCC; however, as the main purpose of the WNADPAR is for ship based application, no interference will occur with commercial devices while operating at open sea and in the confined spaces of the ship.

29

Currently under development, IEEE 802.11n using MIMO technology and UWB, are the standards that provide the highest data rates. By using only IEEE 802.11n standard as the wireless communication link for the full-scale system, it would require approximately 38 WLANs working in parallel (each at 200 Mbps) to provide the 7.68 Gbps that the system demands, as shown in Figure 13. This is based on each T/R module needing 6.4 Mbps and assuming that selective scheduling is used to avoid simultaneous transmit and receive data exchanges.
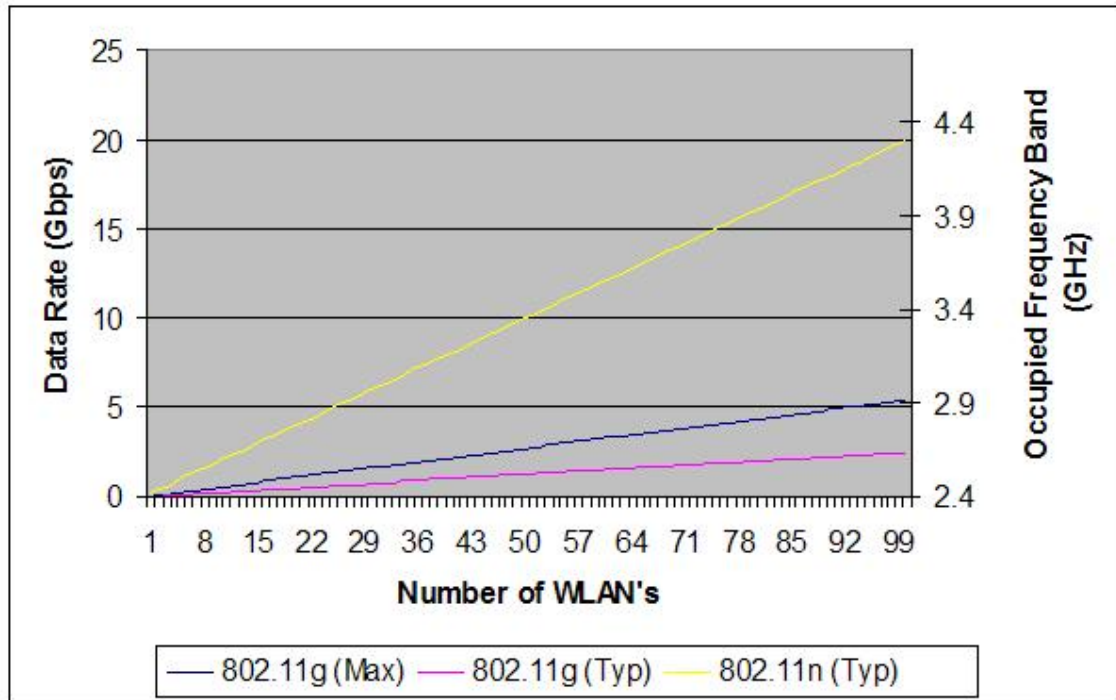
Figure 13.   Number of WLANs operating in parallel vs Data Rate.

On the other hand, UWB offers a data rate of 480 Mbps, but only within a range of 10 meters. This means that a single UWB access point would handle wireless connection with up to 75 T/R modules simultaneously within a radius of 10 meters. A hybrid network might consist of a handful of fiber optic links to remote parts of the ship and short range wireless links at each of the fiber optic terminations.

Therefore, at the present time a combination of both standards represents the most effective approach for the full-scale wireless connection, with UWB connecting elements

in short range (less than 10 meters) and 802.11n for longer range (more than 10 meters) along with a small number of long range fiber optic links. Figure 14 illustrates the theoretical maximum capacity versus range for equivalent UWB and 802.11n channels.
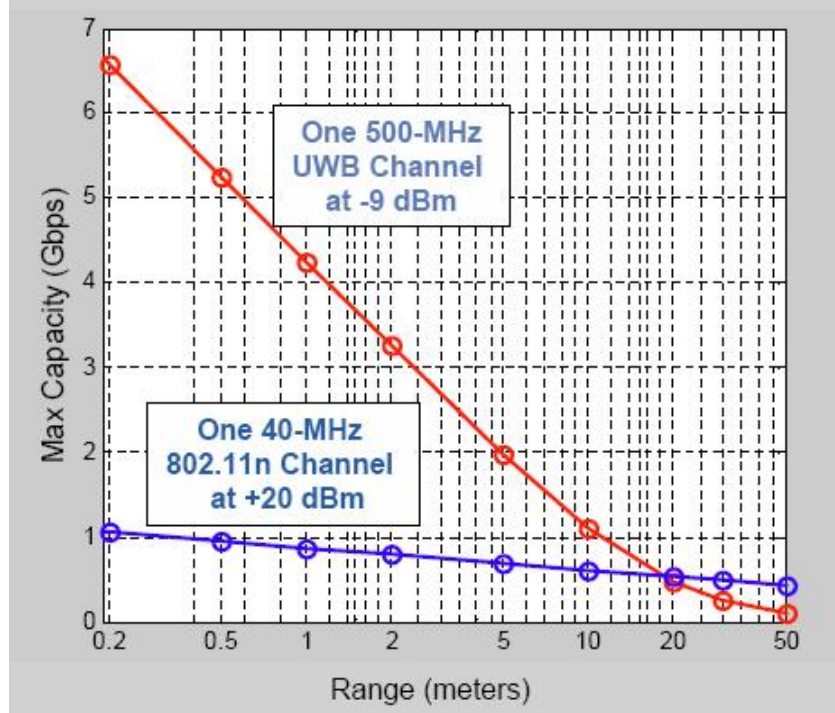
Figure 14.   Maximum capacity for UWB and 802.11n (After [22]).

Furthermore, a high capacity backbone connection is also needed to support the high data rate between the central controller and the large-capacity switches that allow connection with the access points. This requirement can be solved by using 10-Gbps Ethernet standard fiber optic link. The final result is a hybrid switched network that includes optical fiber links and wireless connections with 802.11n and UWB standards.

D.   SUMMARY

This chapter described the various existing and newly developed wireless technologies and guided transmission media. The challenge of the wireless communication between the central controller and the T/R modules was addressed,

having a baseline approach the implementation of a hybrid wireless network that combines the IEEE 802.11n standard to handle T/R modules within a range between 10 and 100 meters from the access points, and UWB standard to handle the array elements within a radius of 10 meters. To obtain wireless coverage over the entire ship will probably require repeaters between compartments. If a high quality wireless channel can not be achieved, then some fiber optic links can be used to remote parts of the ship.

IV. WIRELESS NETWORKING OF A TWO-ELEMENT ARRAY

This chapter describes the details of the wireless networking of the two-element array demonstrator described in [14], including relevant characteristics of the hardware and software employed. Figure 15 illustrates a schematic representation of the physical set up, emphasizing the wireless network aspects with indication of its main components.
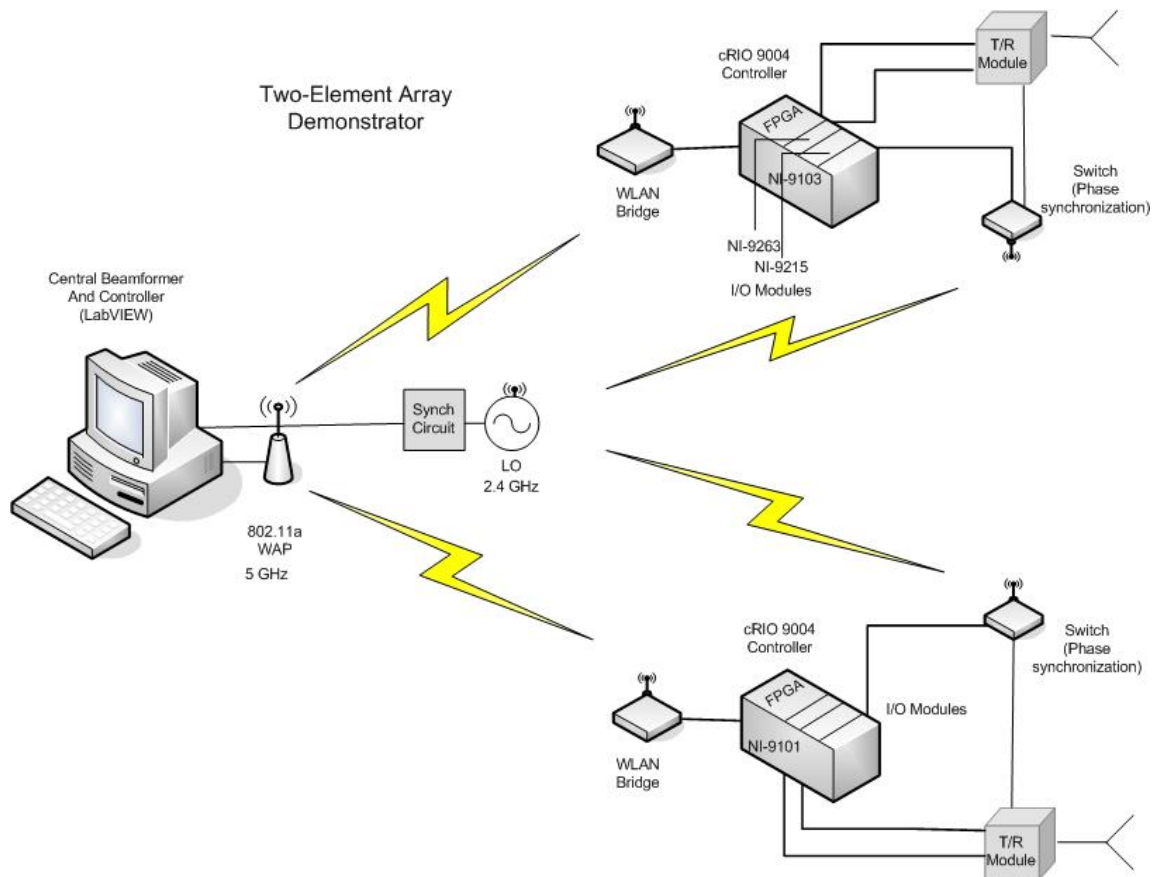
Figure 15.   Two-element array demonstrator wireless networking.

A.   HARDWARE DEVELOPMENT

The hardware required for performing signal processing and control of the T/R modules, as well as the hardware required to wirelessly network the two-element array demonstrator with the central beamformer and controller, are described in the following sections.

1.   CompactRIO Controller

The hardware components used for control and signal processing of the T/R modules are provided by National Instrument (NI).

The National Instruments Compact Reconfigurable Input Output (cRIO) 9004 [25] is an embedded real-time controller that features a 200 MHz Pentium-class processor. This controller contains a 64 MB dynamic random access memory (DRAM) and 512 MB of nonvolatile compact flash storage for data-logging applications. The cRio-9004 controller features a 10/100BaseT Ethernet port for programmatic communication over a network and a RS232 serial port for connection to peripherals such as displays or input devices.

In addition to programmatic communication via Transfer Control Protocol/Internet Protocol (TCP/IP), CompactRIO controllers also include built-in servers for Virtual Instrument Software Architecture (VISA), which is the protocol that provides remote download and communication access to the RIO FPGA over Ethernet. Typical functions of the cRIO-9004 include deterministic control, data logging, and analysis; all functions developed by running LabVIEW Real-Time as operating system. Figure 16 shows a cRIO-9004 real-time controller for illustration purposes.

Figure 16.   NI cRIO-9004 Real-Time Controller (From [25]).

2.   CompactRIO Chassis

The National Instruments CompactRIO reconfigurable chassis [26] is the main part of the CompactRIO system because it includes the reconfigurable input output core. This core contains Field Programmable Gate Arrays (FPGA), which are silicon chips with unconnected logic gates that can define their functionality by using software to configure the FPGA gates.

The reprogrammable FPGA core has an individual connection to each I/O module in its chassis, and can be programmed to read or write signal information from each module. The user-defined FPGA circuitry in the chassis controls each I/O module and passes data to the controller through a local PCI bus, using built-in communication functions. This FPGA core executes LabVIEW control logic at rates up to 40 MHz using single-cycle timed loops, which allows operations precisely synchronized with 25 ns resolution.

In the two-element array demonstrator each module has a separate chassis; one has a NI-9101 chassis and the other a NI-9103 chassis. These are four-slot reconfigurable chassis, and the main difference between them is the amount of logic cells in the FPGA and the available embedded Random Access Memory (RAM). The NI cRIO-9101 is a 1

M chassis with 11,520 logic cells and 82 Kb RAM, and the NI cRIO-9103 is a 3 M chassis with 32,256 logic cells and 196 Kb RAM. Figure 17 illustrates a four-slot NI cRIO-9103 chassis.

Figure 17.   NI cRIO-9103 Embedded Chassis (From [26]).

3.   NI-9263 Module

The NI-9263 [27] is part of the C Series Analog Output Modules from National Instruments. It features built-in signal conditioning and an integrated connector with screw terminal for flexible signal wiring.

The NI-9263 module is a 4-channel, 100 kS/s simultaneously updating analog output module with 16-bit per channel Digital-to-Analog converters that produce the desired output voltage signal. Each channel shares a common ground, which is isolated from the other modules in the chassis, to provide safety and noise immunity.

In the two-element array demonstrator, the NI-9263 module is directly connected to the NI cRIO chassis, where it transmits the desired control and information output signals.

4.   NI-9215 Module

The National Instruments NI-9215 module [28] is part of the C Series Analog Input Modules and includes four simultaneously sampled analog input channels and successive approximation register (SAR) 16-bit Analog-to-Digital converters. The NI

9215 contains a channel-to-earth ground double isolation barrier for safety and noise immunity, and high common-mode voltage range.

The NI-9215 connects directly to CompactRIO FPGA hardware and provides a maximum sampling rate of 100 kS/s per channel with an input signal from ±10 V.

In the two-element array demonstrator, the NI-9215 module is directly connected to the NI cRIO chassis to read the input signals from the receive side of the T/R modules. Figure 18 shows a NI-9263 and a NI-9215 module.

Figure 18.   NI-9263 and NI-9215 Modules (From [27]-[28]).

5.   Access Point

A Wireless Access Point (WAP) is a device that wirelessly connects communication devices to form a wireless network. It usually connects to a wired network, and can relay data between wireless and wired devices.

The two-element array demonstrator is wirelessly connected to the central beamformer and controller with a commercial D-Link WAP model DWL-7100AP. The DWL-7100AP is designed for multimode network deployments with the capability to operate as an Access Point to create a wireless LAN, Point-to-point Bridge to wirelessly connect two networks, Point-to-multipoint Bridge to wirelessly connect multiple

networks, and as a wireless repeater. It is also a dual band device that can assign users to 2.4 GHz or 5 GHz frequency bands, making it compatible with 802.11a, 802.11b, and 802.11g standards.

When the DWL-7100AP is configured to operate as a 5 GHZ 802.11a access point, the operational wireless frequency range goes from 5.15 GHz to 5.35 GHz and from 5.725 GHz to 5.825 GHz based on selected channel. When it is configured to work as a 2.4 GHz 802.11b/g access point, the operational frequency range goes from 2.4 GHz to 2.4835 GHz [29]. This access point was designed to deliver a wireless performance with maximum wireless signal rates reaching up to 108 Mbps when set in turbo mode for both 802.11g and 802.11a networks. However, this is a theoretical data throughput while the real data rate capacity is approximately 54 Mbps, mainly because of the network conditions and environmental factors. An access point with these characteristics can handle up to 8 T/R modules based on the estimate of 6.4 Mbps per module for the demonstration array. Figure 19 shows a D-Link WAP DWL-7100AP for illustration purposes.

Figure 19.   Wireless Access Point (From [29]).

6. Ethernet Bridge

A network bridge is a device that connects multiple network segments, functioning similar to repeaters or network hubs, but using bridging where traffic from one network is managed rather than simply rebroadcast to adjacent network segments.

Each one of the T/R modules in the two-element array demonstrator is wirelessly connected to the central controller via the WAP by using a 3Com Wireless LAN Bridge [30]. The wireless bridge supports IEEE 802.11a (5 GHz) and b/g (2.4 GHz) networking standards with the capability to handle up to 16 Ethernet wired connections, when paired with a 16-port switch. The wireless bridge includes internal dual-diversity antennas, and an external connector that allows an optional dual-band omni-directional antenna to be connected to extend the wireless transmission range.

The media interfaces included in the wireless bridge consists of a DB9 serial port and a RJ-45 port to connect to an Ethernet device. Figure 20 shows a 3Com Wireless LAN Bridge.

Figure 20.   Wireless LAN Bridge (From [30]).

B.   PROGRAM DEVELOPMENT IN LABVIEW

LabVIEW stands for Laboratory Virtual Instrument Engineering Workbench. It is application software developed by National Instruments based on graphical programming. LabVIEW has built-in libraries for using software standards such as TCP/IP networking.

With LabVIEW it is possible to create test, measurement, control and automation applications. A graphical user interface (GUI) can also be created to control various parameters in the simulated system.

There are two main parts in a LabVIEW FPGA system: the LabVIEW FPGA module and the RIO hardware. The LabVIEW FPGA module extends the LabVIEW environment to develop virtual instruments (VIs) to be implemented as hardware in the FPGA on RIO hardware. On the RIO hardware platforms, the FPGA defined the device functionality which allows using software to define the device functionality. Figure 21 depicts the architecture of a LabVIEW FPGA system.
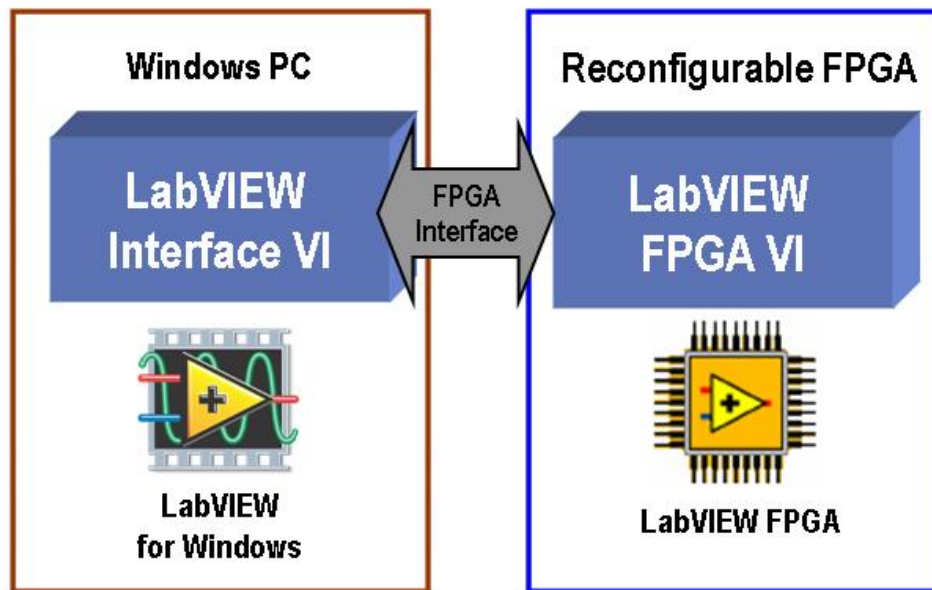
Figure 21.   LabVIEW FPGA architecture (From [31]).

1.   Software Model

Figure 22 depicts the basic steps to develop a LabVIEW FPGA application. These steps are the following [31]:

- Configure hardware in project. A LabVIEW project is used to manage and configure all resources for FPGA devices.

- Create FPGA resources. After the hardware has been configured, all the necessary resources for the application need to be added to the project.

- Build the FPGA virtual instrument (VI). The FPGA VI is first built on the host computer.

- Compile the FPGA VI. The FPGA VI code on the host computer needs to compile before executing on the FPGA.

- Build the host interface. The last step is to create the host interface which integrates the FPGA hardware with the rest of the measurement and control system.
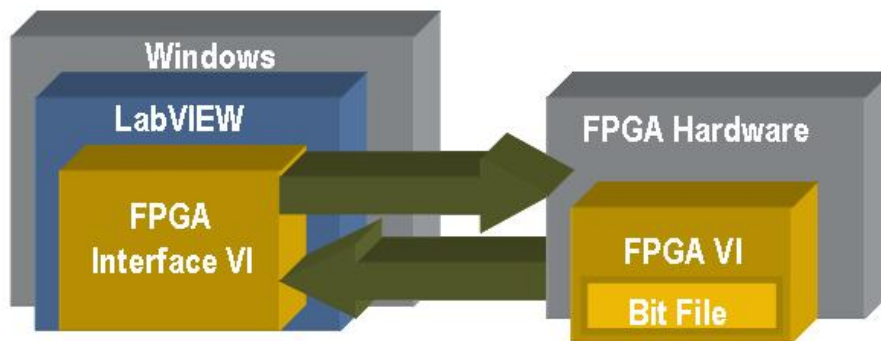
Figure 22.   LabVIEW FPGA model (After [31]).

2.   Project Organization

The LabVIEW project created to wirelessly control the operation and data communication between the central controller and the two T/R modules is organized as shown in Figure 23.

Running on the host computer there are three VIs. The host interface file, called "TxRxDemonst_FD.vi," is the main program that works as link, monitor, and control of the FPGA system. The files "Convert to Binary.vi" and "Convert to Voltage.vi" are support files provided by the National Instruments library. These two files convert all I/O values from a nominal value to a matching binary value or vice versa to be correctly interpreted by the FPGA device.

The two cRIO-9004 real-time controllers along with the cRIO-9001/3 embedded chassis of each T/R module were added to the project as FPGA targets. They were programmed as "CRIORAD1" and "CRIORAD2" with internet protocol (IP) address 169.254.0.9 and 169.254.0.8 respectively.

Each FPGA target has two C Series (cRIO) modules available, NI-9263 in slot 1 of the chassis and NI-9215 in slot 2, to control data exchange during I/O operations.

The cRIO modules have special calibration constants that must be taken into consideration when calculating a corresponding binary value. These calibration constants are used by the host application to scale the data to calibrated voltage values. Downloaded into each one of the FPGAs there are three VIs which main tasks are: (1) obtain the calibration constants, (2) enable the host interface file the capability to read data from the analog input module NI-9215, and (3) enable the host interface file the capability to write data to the analog output module NI-9263.

FIFO is one of the functions used in LabVIEW FPGA for applications that require high speed data acquisition. This function allows buffering the data in the FPGA memory space and transferring it to the host processor without loss.
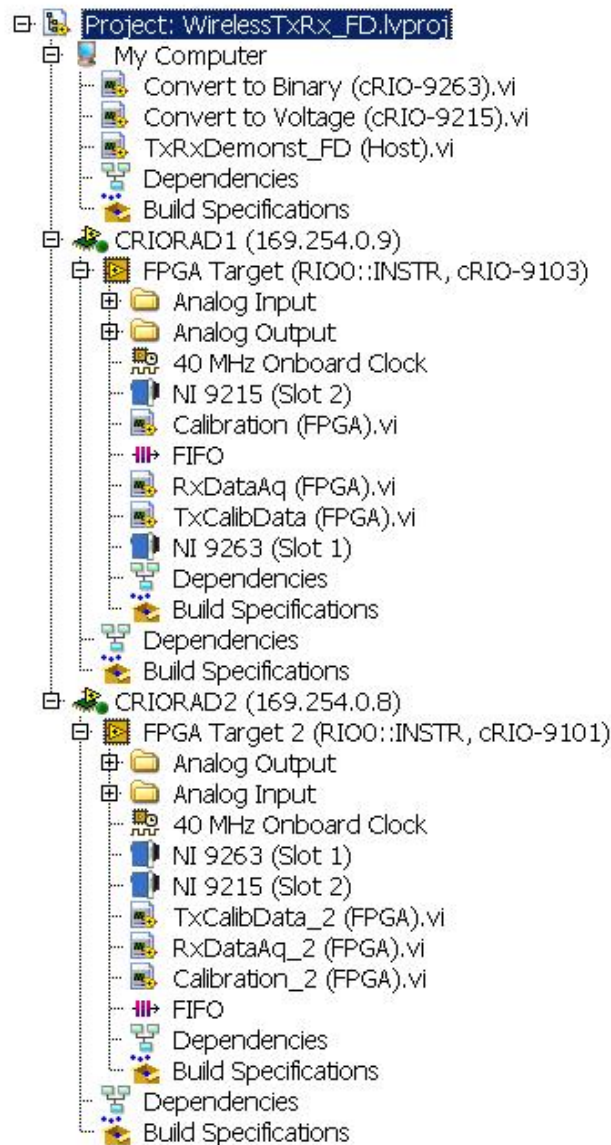
Figure 23.   Project organization.

3.   Interface

The user interface was designed to control the transmission signals and to record and display the input data from each T/R module. It is basically divided into four blocks as shown in Figure 24. Blocks 1 and 3 control the output signals on the transmit phase of the T/R modules 1 and 2 respectively, while blocks 2 and 4 record the input data signals

on the receive phase. Each block has an On/Off switch that needs to be turned on before running the program if the operation of a given block is desired.

On the transmit control block, there are two controls to adjust the amplitude (A) and phase (θ) of the transmitted signal. There are also four numeric indicators that present the corresponding in-phase (I) and quadrature-phase (Q) components for the values of phase and magnitude introduced. These components are given by

$$I = A\cos\theta$$
$$Q = A\sin\theta \tag{3}$$

There are three more controls that allow the user to vary the frequency, duty cycle and number of points per waveform cycle. By controlling the frequency (f_P) and duty cycle, it is possible to determine the number of samples per pulse width (N_s). This is given by

$$N_s = \left(f_{sampling}\right)\left(duty\_cycle\right)\left(\frac{1}{f_P}\right) \tag{4}$$

where $f_{sampling}$ is the maximum sampling rate equal to 100 kS/s for this specific hardware. The number of samples per pulse width needs to be greater than two if a sampling loss under 0.2 dB is desired [15].

Finally, also on blocks 1 and 3, there is a waveform chart that shows the instantaneous I and Q components been transmitted for the NI-9263 module.

On receive side, blocks 2 and 4, consist of three waveform charts. The first chart, shows the average input voltage of the I and Q components that have been received by the NI-9215 module from the T/R module. The second and third charts show the average phase and average magnitude values. The averages are taken over the most recent 100 samples.

The corresponding phase and magnitude values are calculated by

44

$$\theta = \arctan\left(\frac{Q}{I}\right)$$

$$A = \sqrt{I^2 + Q^2}$$

(4)
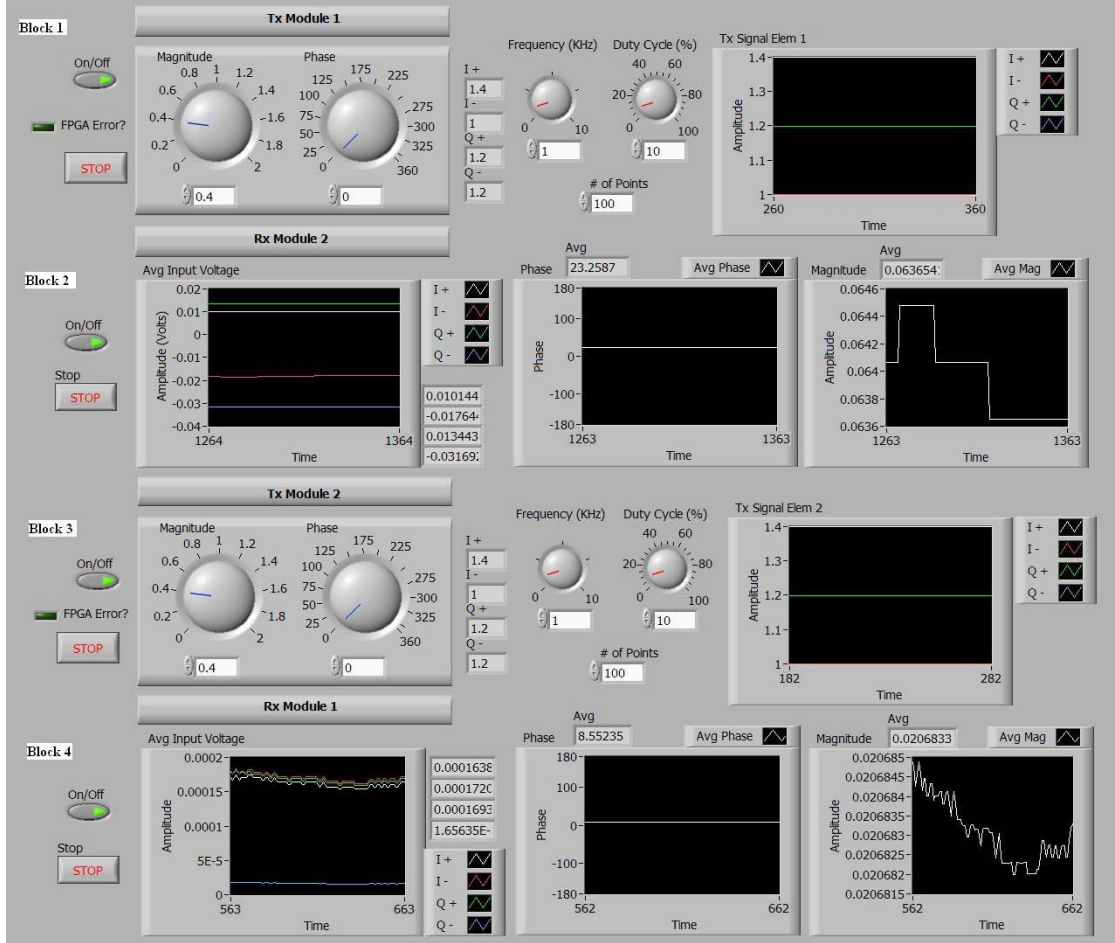
Figure 24.   Program graphic user interface.

C.   SUMMARY

This chapter described the hardware and software development for the wireless networking of a two-element array demonstrator. The main characteristics of every piece of hardware needed in the demonstrator were presented. A detailed description of the software model and project organization was also shown.

The next chapter describes the procedure conducted to measure the performance of the two-element array demonstrator while operating wirelessly.

V. SET UP AND MEASUREMENTS OF THE WIRELESS DEMONSTRATOR

Chapter IV presented the main characteristics of the hardware and software used for the wireless networking of a two-element array demonstrator.

This chapter presents the tests developed to assess the performance of the two-element array demonstrator while operating wirelessly. The general set up used during the tests is explained along with the measurements conducted to determine the output phase response based on a change in the input phase, and the latency of the system.

A. SET UP

In the two-element array demonstrator a computer running LabVIEW 8.2 acts as the central beamformer and controller. This computer is connected to a D-Link WAP with an Ethernet crossover cable. The WAP is configured to operate in the 802.11a wireless standard at the 5 GHz frequency band, in order to avoid interference with the LO and many other WiFi devices operating at the 2.4 GHz frequency band.

Each NI cRIO-9004 real-time controller is connected to a wireless network bridge with a standard Category 5 unshielded twisted pair (UTP) Ethernet cable. The 3Com wireless network bridges are configured to operate in infrastructure mode with the auto select option enabled. This means that they are configured to work wirelessly in conjunction with a WAP and they will automatically select the best channel to work with. This channel could be either the channel with the least number of packets or the channel in use by the WAP.

The eight terminals corresponding to four channels (I+, I-, Q+, and Q-) in the modulator and the demodulator boards in the T/R modules are physically connected the NI-9263 analog output module and NI-9215 analog input module respectively.

The LO signal is provided by an external source calibrated at frequency 2.4 GHz and power of about +4 dBm. This LO signal is divided by a two-way power divider into

two equal signals to feed the hardwired LO port of each one of the T/R modules. The final signal power into the AD8346 and AD8347 boards is approximately -8 dBm as required by the manufacturer in the devices' data sheets [32]-[33]. The hardware components of one antenna element are shown in Figure 25.
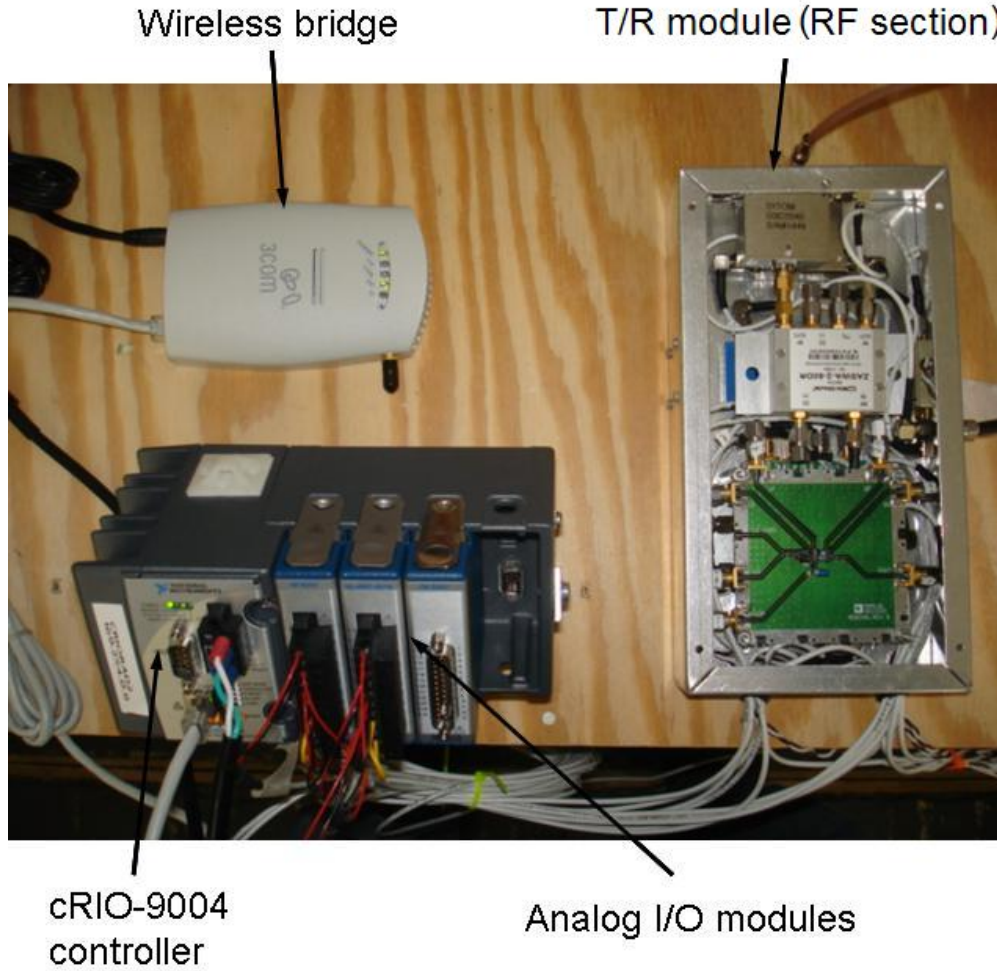
Figure 25.   Antenna element.

B.   PHASE AND AMPLITUDE TRANSMISSION MEASUREMENT

1.   Calibration Data

Every AD8347 demodulator board has an individual dc offset that needs to be calculated and corrected for in the processing. The resulting I and Q data offset from the

calibration process, presented in [13], can be digitally corrected in the host interface file by using an adaptive Matlab script in LabVIEW. The calibration data was recorded to determine the offset of the demodulator boards in T/R modules 1 and 2. The resultant voltages are shown in Tables 3 and 4.

Set Phase	I +	I -	Q +	Q -
0	1.014	1.002	0.993	1.025
30	1.005	1.008	0.989	1.029
60	0.992	1.021	0.986	1.032
90	0.98	1.034	0.99	1.028
120	0.979	1.042	1	1.017
150	0.972	1.043	1.012	1.005
180	0.979	1.038	1.028	0.994
210	0.984	1.026	1.032	0.989
240	0.993	1.015	1.033	0.989
270	1.01	1	1.028	0.992
300	1.017	0.998	1.017	1.004
330	1.018	0.995	1.005	1.014

Table 3.   Calibration data for demodulator board in T/R module 1.

Set Phase	I +	I -	Q +	Q -
0	0.99	1.026	0.996	1.021
30	0.981	1.04	1.001	1.013
60	0.97	1.048	1.011	1.005
90	0.973	1.048	1.024	0.991
120	0.974	1.043	1.037	0.979
150	0.982	1.031	1.043	0.974
180	0.992	1.021	1.048	0.974
210	1.008	1.008	1.036	0.98
240	1.016	1	1.029	0.987
270	1.016	1.001	1.015	1.001
300	1.016	1.006	1.006	1.012
330	1.005	1.014	0.998	1.021

Table 4.   Calibration data for demodulator board in T/R module 2.

Figure 26 shows the I/Q circles generated after the calibration data with indication of the offset values that need to be incorporated into Equation (4) in order to get the correct phase on the receive side of the T/R modules.
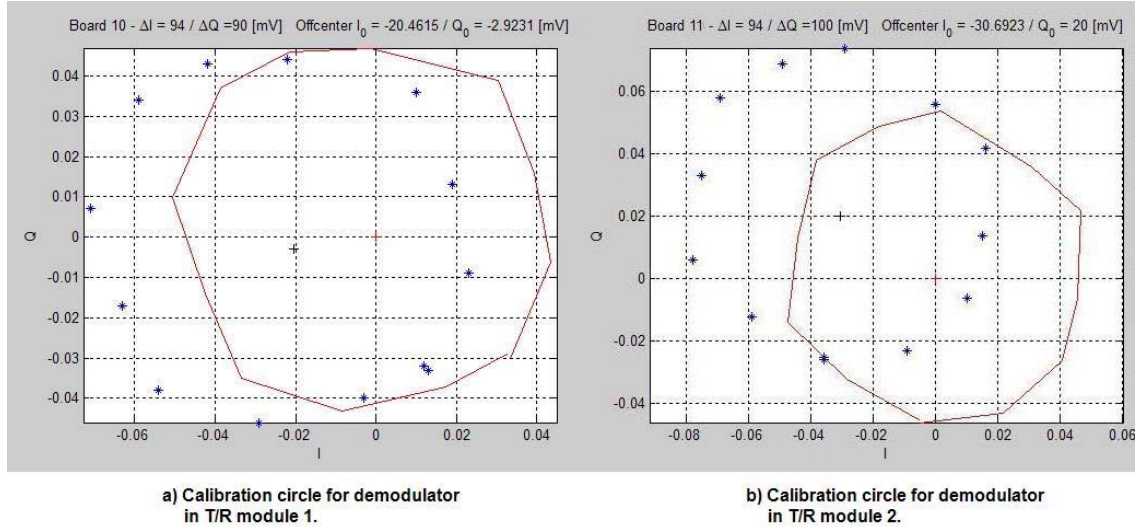
Figure 26. Plotted demodulator boards calibration data (solid lines show the data with the offset removed).

The calculated offset values for demodulator board in T/R module 1 are $I_o = -20.4615$ mV, $Q_o = -2.9231$ mV and for T/R module 2 are $I_o = -25.6923$ mV, $Q_o = 21.6923$ mV. These values are added to the calculated phase on the receive side of the LabVIEW host interface file.

2. Phase Transmission Measurement

The two purposes of this test were to (1) verify the correct operation of the two-element array demonstrator while working wirelessly, and (2) corroborate the linear relationship between the input phase signal into the AD8346 modulator board and the output phase signal from the AD8347 demodulator board.

This test was conducted twice. The first time to test data transmission from T/R module 1 with reception of the signal in T/R module 2, and the second one transmitting from T/R module 2 to 1.

The RF input signal to the AD8346 modulator board was modulated and controlled with the Phase and Magnitude control knobs in the LabVIEW control software. The magnitude was set to 1 volt and the phase was changed from 0 to 350 degrees in 10 degrees increments. Voltage readings were taken from the I+, I-, Q+, and

Q- indicators in the user interface of the LabVIEW host program. The received phase from the AD8347 demodulator board was recorded from the average phase indicator, which gives the average based on the 100 most recent samples. Its value was also verified by first calculating the differential I and Q voltages and then applying these differential values to Equation (4). The results obtained are tabulated in Tables 5 and 6.

Input Phase	I +	I -	Q +	Q -	Amplitude (mV)	Output Phase
0	1	1.015	0.989	1.022	56	101.06
10	1.005	1.011	0.995	1.018	51	113.78
20	1.008	1.007	0.998	1.014	48	125.30
30	1.011	1.004	1.001	1.012	47	135.00
40	1.014	1.002	1.004	1.009	50	144.70
50	1.016	1	1.007	1.006	50	153.60
60	1.018	0.998	1.01	1.002	50	163.32
70	1.021	0.995	1.015	0.998	55	174.81
80	1.021	0.994	1.02	0.994	57	184.67
90	1.02	0.996	1.025	0.989	54	196.06
100	1.017	0.998	1.029	0.984	56	207.54
110	1.014	1.001	1.032	0.981	55	217.14
120	1.011	1.003	1.037	0.977	55	228.67
130	1.008	1.007	1.04	0.975	53	238.35
140	1.005	1.011	1.042	0.972	54	247.82
150	1	1.015	1.044	0.97	55	258.45
160	0.995	1.02	1.045	0.97	54	269.26
170	0.992	1.025	1.044	0.969	58	277.81
180	0.988	1.029	1.043	0.97	55	286.61
190	0.983	1.034	1.043	0.972	55	297.17
200	0.979	1.037	1.041	0.973	56	304.90
210	0.974	1.04	1.039	0.975	57	313.61
220	0.972	1.041	1.035	0.977	54	320.02
230	0.97	1.046	1.031	0.982	52	331.51
240	0.969	1.048	1.028	0.984	52	337.29
250	0.967	1.05	1.024	0.988	51	345.98
260	0.966	1.049	1.019	0.995	53	357.69
270	0.968	1.049	1.015	0.998	51	4.85
280	0.969	1.047	1.011	1.002	48	13.64
290	0.971	1.044	1.007	1.006	46	23.62
300	0.973	1.041	1.002	1.009	45	34.14
310	0.978	1.038	1	1.013	43	45.32
320	0.983	1.033	0.997	1.015	42	58.52
330	0.986	1.028	0.992	1.01	48	67.66
340	0.991	1.024	0.988	1.026	59	83.02
350	0.996	1.019	0.985	1.028	60	92.38

Table 5.   Measured data transmitted from T/R module 1 to 2.

Input Phase	I +	I -	Q +	Q -	Amplitude (mV)	Output Phase
0	1.007	1.004	0.989	1.028	42	123.04
10	1.01	1.001	0.99	1.026	44	131.69
20	1.012	0.999	0.993	1.023	41	141.02
30	1.014	0.997	0.997	1.02	43	151.81
40	1.016	0.995	1	1.016	42	162.49
50	1.017	0.993	1.004	1.013	44	172.22
60	1.016	0.994	1.009	1.008	43	185.28
70	1.018	0.993	1.013	1.004	45	194.70
80	1.016	0.995	1.017	1.001	46	204.53
90	1.014	0.997	1.021	0.997	45	215.70
100	1.012	1	1.023	0.994	46	224.52
110	1.01	1.002	1.026	0.991	49	233.11
120	1.006	1.006	1.029	0.989	46	244.51
130	1.003	1.009	1.03	0.988	46	252.16
140	0.999	1.013	1.031	0.987	45	262.16
150	0.995	1.017	1.031	0.987	47	271.88
160	0.99	1.021	1.031	0.987	48	282.66
170	0.986	1.026	1.03	0.987	49	293.05
180	0.983	1.028	1.027	0.99	46	301.58
190	0.98	1.031	1.026	0.992	47	309.59
200	0.977	1.034	1.022	0.995	48	320.68
210	0.975	1.036	1.019	0.998	47	329.45
220	0.974	1.037	1.015	1.001	46	338.31
230	0.973	1.039	1.011	1.005	46	348.91
240	0.972	1.039	1.007	1.01	46	0.09
250	0.973	1.039	1.003	1.013	45	8.83
260	0.974	1.038	0.999	1.018	46	20.27
270	0.975	1.035	0.995	1.022	45	31.34
280	0.977	1.033	0.992	1.024	44	39.29
290	0.981	1.031	0.99	1.026	43	48.23
300	0.985	1.028	0.988	1.029	43	59.38
310	0.987	1.024	0.988	1.03	41	67.06
320	0.992	1.019	0.985	1.031	43	81.37
330	0.997	1.015	0.984	1.031	41	93.20
340	1	1.01	0.986	1.031	43	103.96
350	1.004	1.007	0.986	1.031	46	112.54

Table 6.   Measured data transmitted from T/R module 2 to 1.

A comparison between the ideal phase response and the actual phase response when transmitting between T/R modules 1 and 2 is presented in Figures 27 and 28 respectively. For this measurement both the power amplifier (PA) and low noise amplifier (LNA) were by-passed in the T/R modules. The ideal phase response is

achieved when a perfect linear relationship between the transmitted and the received phase signals exit, while the measured response shows a very small deviation between them.

In Figure 27, the phase error when transmitting from T/R module 1 to T/R module 2 is shown. The plot shows that the transmitted and received phases are almost identical with a small deviation between them.

From data on Table 5 it is possible to determine that a constant offset of about -79 degrees is induced in the system. This constant offset is expected due to several connectors, attenuators, and cables within the T/R modules; however it can be determined and compensated for in the beamforming. The maximum phase error registered during this test was approximately 6.2 degrees.

This error can be attributed to measurement errors and hardware errors. Also these are second order effects such as mismatch and multiple reflections that can result in errors of this magnitude.
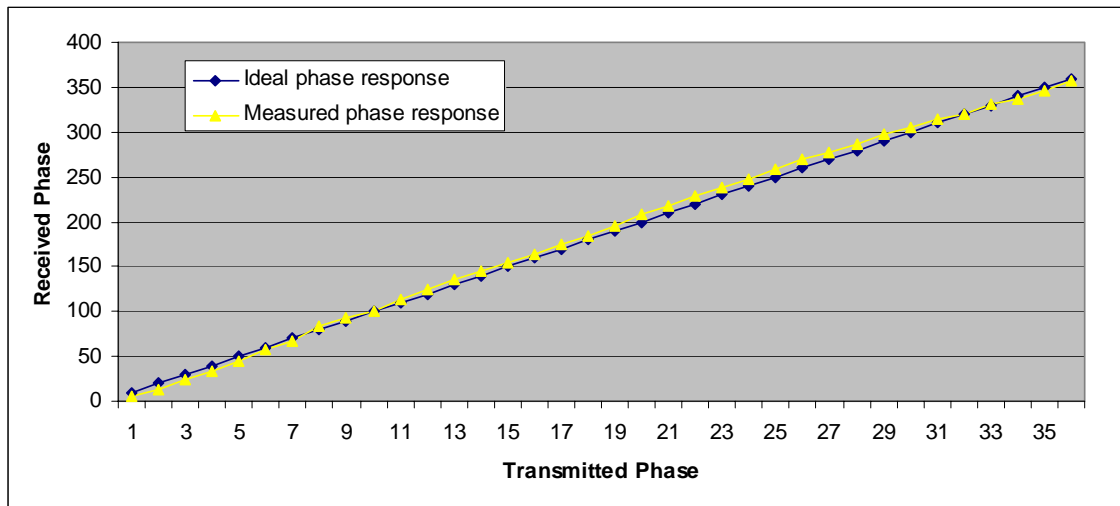

Figure 27.   Phase response transmitting from T/R module 1 to 2.

The phase errors when transmitting from T/R module 2 to T/R module 1 are shown in Figure 28. In this case, the phase errors are also negligible having the maximum

phase error an approximately value of 5.9 degrees. The induced offset between T/R module 2 and T/R module 1 is about -57 degrees.

This test shows that the T/R modules and the control software implemented in LabVIEW are functioning as required while operating wirelessly; however, the system is very sensitive and needs to be correctly calibrated mainly with respect to the power levels into the amplifiers, LO ports, and demodulator RF inputs in order to get the best results.

These phase errors are small enough so that they will not degrade the array's performance.
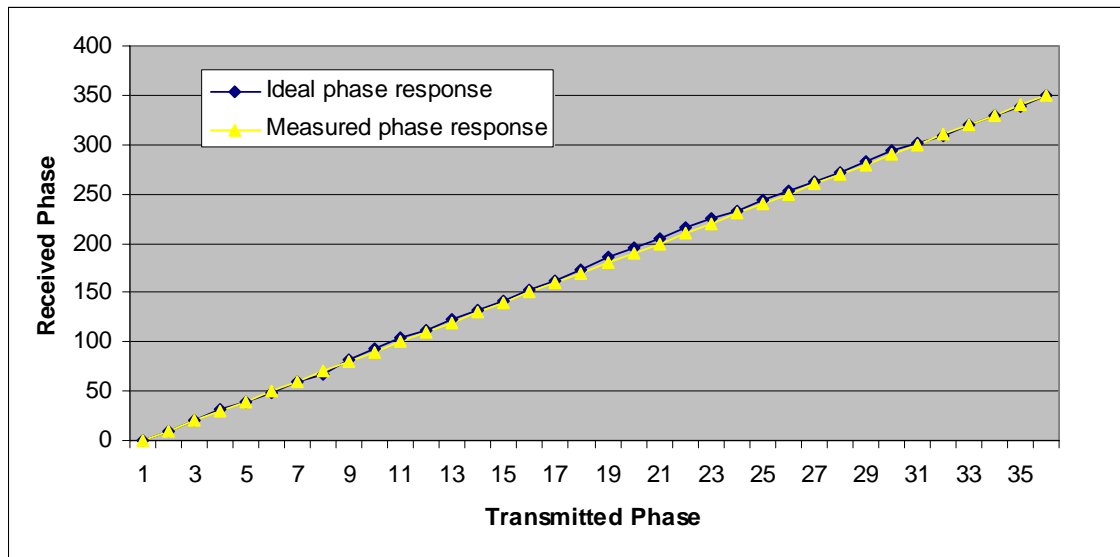
Figure 28.   Phase response transmitting from T/R module 2 to 1.

C.   WIRELESS SYSTEM LATENCY

Latency is the time delay caused by getting the information data from the central beamformer and controller to the antenna elements, and getting a response back again. High latency times cause noticeable performance degradation in any system.

For the full-scale radar system, the three major contributors to be considered when estimating the latency time are (1) the response time of the electronic components, (2) the processing time, and (3) the latency time in the wireless links between the central beamformer and controller and all the remote T/R modules.

The main factors that can cause an increment in latency times are [34]:

- Propagation delay: this varies with the total end-to-end length of the network connection. For signals propagation is limited by the phase velocity in the medium and the speed of light in free space.

- Transmission delay: the time taken to transmit a packet on each hop of a connection. This delay depends on the bandwidth of the connection in bits per second.

- Router delays: data packets are re-assembled when received by routers, and then buffered in memory until they can be transmitted on the hop to the next router. If that next hop is congested, the packet can be delayed inside the router for long periods.

- Packet loss, recovery, and re-transmission: the TCP protocol automatically takes care of these actions; however, there is a time delay while fixing one of these issues.

When estimating the latency time for the full-scale radar system, the last point could be ignored. The communication protocol needs to ignore a packet lost and continue the transmission/reception of the rest of the packets to avoid an increment in the latency time and an increased delay of the signal processing. Data packets lost from a small number of antenna elements will not significantly affect the beamforming when hundreds or thousands of elements are used.

The latency time in the wireless links between the central controller and each one of the T/R modules in the two-element array demonstrator was measured by executing the ping command inside a command window. The time measured is the round-trip time (RTT), it is expressed in milliseconds and it is the time it takes for a ping request to be sent and replied to. RTT represents the latency of the signal path between the central controller and the specified T/R module. Tables 7 and 8 summarize the latency measurements by using four ping trials on T/R modules 1 and 2 respectively.

Reply from	Bytes	Time	Time to Live (TTL)
169.254.0.9	32	3 ms	60
169.254.0.9	32	1 ms	60
169.254.0.9	32	1 ms	60
169.254.0.9	32	1 ms	60

Table 7.   Latency to T/R module 1 with 32 bytes of data.

Reply from	Bytes	Time	TTL
169.254.0.8	32	3 ms	60
169.254.0.8	32	1 ms	60
169.254.0.8	32	1 ms	60
169.254.0.8	32	1 ms	60

Table 8.   Latency to T/R module 2 with 32 bytes of data.

The average RTT measured during the first test to T/R modules 1 and 2 was 1 millisecond. This is a rather unrealistic test because the test packet of 32 bytes is too small. To perform a more realistic test, a bigger test packet can be used by incorporating the parameter "-l 1472" to the ping command. The results of this test are shown in Tables 9 and 10.

Reply from	Bytes	Time	TTL
169.254.0.9	1472	3 ms	60
169.254.0.9	1472	2 ms	60
169.254.0.9	1472	2 ms	60
169.254.0.9	1472	2 ms	60

Table 9.   Latency to T/R module 1 with 1472 bytes of data.

Reply from	Bytes	Time	TTL
169.254.0.8	1472	4 ms	60
169.254.0.8	1472	2 ms	60
169.254.0.8	1472	2 ms	60
169.254.0.8	1472	2 ms	60

Table 10.   Latency to T/R module 2 with 1472 bytes of data.

In this case, the average RTT is approximately 2 milliseconds for both T/R modules. This latency is really significant if compared with the FPGA clock that runs at 40 MHz. This means that one tick of the FPGA clock is equal to 25 nanoseconds and the latency time from the central controller to one T/R module (i.e., one way path) corresponds approximately to 40,000 ticks. However, the data acquisition and transmission processes require much longer than just one tick of the clock and by using the FIFO function on the receive side of the FPGA VI, it prevents the lost of information when buffering the data in the FPGA memory space and transferring it to the host processor.

In the full-scale radar system, latency time is an important factor that needs to be precisely determined, minimized as much as possible, or compensated for when processing the signal. The latency time affects the time response of the radar and it can also affect the determination of the threshold setting for the time of arrival.

One option to be considered in order to minimize the latency time in the full-scale system is the implementation of the Point Coordination Function (PCF) as media access control technique. PCF enables the transmission of time-sensitive information by incorporating a point coordinator within the access point to control which antenna elements can transmit during any given period of time. Thus, PCF enables antenna elements to transmit data packets synchronously and eliminates collision problems. In the two-element array demonstrator the Distributed Coordination Function (DCF) is in use because it is the default setting for the WiFi commercial hardware.

A second possibility is the implementation of Time Division Duplex (TDD) in the communication links. This technique emulates a full-duplex communication over a half duplex communication link and increases the flexibility and capacity of the system. The main advantage of this technique is in the case where the uplink and downlink data speed is variable, like in the full-scale radar system where the amount of control data sent from the central beamformer and controller to the antenna elements is small compared with the echo data sent from the antenna elements to the central controller.

D.   SUMMARY

This chapter presented the tests and measurements conducted to assess the wireless communication between the central beamformer and controller and two T/R modules. First, calibration data was obtained to compensate for the offset generated at the AD8346 demodulator boards in each T/R module. Second, the linearity between the input phase and the output phase was verified when transmitting one RF signal from one T/R module to the other. All the control signals were passed wirelessly between the central controller and the T/R modules with satisfactory results. Finally, the latency time generated when transmitting wirelessly a test packet was also measured.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The Wirelessly Networked Aperstructure Digital Phased Array Radar (WNADPAR) applies three relatively new concepts. The Opportunistic concept is based on placing the antenna elements at available open areas over the entire length of the ship. Based on the Aperstructure concept, the full length of the ship effectively becomes the aperture of the phased array radar. The Wirelessly Networked Digital Architecture concept aims to implement stand-alone modules at each antenna element wirelessly networked to a central processor with the power supply as the only wired connection.

The objective of this thesis was to address the challenge of the wireless communication in a Wireless Networked Aperstructure Digital Phased Array Radar. The use of wireless networks as beamformers has many advantages over conventional arrays using microwave circuits. Wireless networks as beamformers make a radar system more adaptable to the operational environment, survivable and very flexible.

The main concerns for the shipborne application of the wireless network are the long range and high data rate wireless connectivity internal to the ship. These problems are important because the wireless network requires a good quality propagation channel among the central controller and all the antenna elements.

Several network configurations were discussed in this research that can potentially reduce the propagation problems:

- Incorporate relays between compartments.

- Use hardwire connections to the elements (optical or RF).

- Combine a small number of hardwire runs to remote parts of the ship with short range wireless links at each of the terminations.

- Employ a transmission system that is integrated into the ship structure.

Along with the different network configurations, a survey of the existing and newly developed wireless technologies and guided transmission media was conducted.

Analysis of the network configurations incorporating different wireless technologies suggests as a baseline approach the implementation of a hybrid wireless network. This network requires a combination of the 802.11n standard to handle antenna elements within a long range (greater than 10 meters) and UWB standard for those antenna elements within a short range (less than 10 meters), as well as the use of several repeaters between compartments and fiber optic links to remote parts of the ship to ensure a high quality wireless channel all around the ship.

For simulation and demonstration purposes of the full-scale radar system, a two-element array demonstrator was wirelessly networked by using commercial devices. One wireless access point by D-Link was connected to the central controller and beamformer and two wireless network bridges by 3-Com were connected to the cRIO-9004 real-time controllers to allow wireless communication between the central controller and each T/R module. This network was configured to operate in the IEEE 802.11a standard at 5 GHz frequency band to avoid any possible interference with the LO set to operate at 2.4 GHz and any other WiFi device operating in the 802.11b/g standards.

For control and monitoring of the two-element array operation, a software program was developed using LabVIEW 8.2. This program allows the simultaneous operation of both T/R modules, controlling on the transmission phase the amplitude and phase of the signal, as well as the frequency, duty cycle, and number of points per waveform cycle. On receive side, the program records and display on three different waveform charts the signal average input voltage of the I and Q components, the average phase, and the average magnitude, respectively.

Finally, the performance of the two-element array demonstrator was measured while operating wirelessly. Different tests were conducted to verify the linear phase response between the antenna elements, as well as the latency time in the wireless links. Satisfactory results were obtained after testing, with a maximum phase error of about 6.2 degrees and the average latency time of 1 millisecond.

B. RECOMMENDATIONS FOR FUTURE WORK

1. Latency Time

The latency time was measured in the wireless communication of a two-element array demonstrator. Effort should be made to simulate the wireless/wired links of a full-scale radar system and estimate the latency time among them. Different approaches to reduce the latency of the wireless network should be investigated as well. One of such approaches consists of reducing the amount of data that needs to be transmitted between the central controller and the T/R modules by incorporating more processing or hardware capability at each T/R module.

2. Eight-element Array

After demonstrating the correct wireless operation of the two-element array demonstrator, an eight-element array could be developed to extend the demonstration array. Six more T/R modules need to be assembled and the control software in LabVIEW need to be further expanded to incorporate in the same project a reference to every cRIO-9004 controller corresponding to each T/R module to be added to the array. Measurements and tests of the demonstrator would be necessary to assess its performance in comparison with the two-element array, determining if any degradation of the signal processing exits.

3. Multiple Chassis Synchronization

In the case of the eight-element array demonstrator, selective scheduling is needed to avoid simultaneous transmit and receive data exchanges from each T/R module. This is in order to reduce the required throughput in the wireless links and succeed in the implementation of the demonstrator using actual commercial wireless technology. There are different methods recommended by National Instruments to synchronize the NI cRIO-9001/3 embedded chassis that need to be investigated and implemented.

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LIST OF REFERENCES

[1]   BBC News, "North Korea's missile programme," http://news.bbc.co.uk/2/hi/asia-pacific/2564241.stm, last retrieved July 2007.

[2]   Missile Defense Agency, "A Layered Integrated Defense," BMDS booklet, fourth edition, 2007.

[3]   Naval Technology, "DDG 1000 Zumwalt Class – Multimission destroyer," http://www.naval-technology.com/projects/dd21/, last retrieved July 2007.

[4]   Program Executive Office Ships, "Navy Designates Next-Generation Zumwalt Destroyer," http://peoships.crane.navy.mil/ddg1000/dodreleasenns060407.htm, last retrieved July 2007.

[5]   David C. Jenn, "Distributed phased arrays and wireless beamforming networks," Program Review, Naval Postgraduate School, January 2007 (unpublished).

[6]   Lance C. Esswein, "Genetic algorithm design and testing of a random element 3-D 2.4 GHz phased array transmit antenna constructed of commercial RF microchips," Master's Thesis, Naval Postgraduate School, Monterey, California, June 2003.

[7]   Cher S. Eng, "Digital antenna architectures using commercial off the shelf hardware," Master's Thesis, Naval Postgraduate School, Monterey, California, December 2003.

[8]   Chin S. Ong, "Digital phased array architectures for radar and communications based on off-the-shelf wireless technologies," Master's Thesis, Naval Postgraduate School, Monterey, California, December 2004.

[9]   Winston Ong, "Commercial off the shelf direct digital synthesizers for digital array radar," Master's Thesis, Naval Postgraduate School, Monterey, California, December 2005.

[10]   Chin H. M. Tong, "System study and design of broad-band U-slot microstrip patch antennas for aperstructures and opportunistic arrays," Master's Thesis, Naval Postgraduate School, Monterey, California, December 2005.

[11]   Yoke C. Yong, "Receive channel architecture and transmission system for digital array radar," Master's Thesis, Naval Postgraduate School, Monterey, California, December 2005.

[12]   Yong Loke, "Sensor synchronization, geolocation and wireless communication in a shipboard opportunistic array," Master's Thesis, Naval Postgraduate School, Monterey, California, March 2006.

[13]   Gert Burgstaller, "Wirelessly networked digital phased array: design and analysis of a 2.4 GHz demonstrator," Master's Thesis, Naval Postgraduate School, Monterey, California, September 2006.

[14]   Eng C. Yeo, "Wirelessly networked opportunistic digital phased array: system analysis and development of a 2.4 GHz demonstrator," Master's Thesis, Naval Postgraduate School, Monterey, California, December 2006.

[15]   Merrill I. Skolnik, *Introduction to Radar Systems*, third edition, pp. 80-87,559-567, McGraw-Hill, New York, 2001.

[16]   Northrop Grumman Corporation, "Zumwalt (DDG 1000)," http://www.ddg1000.com/pressroom/, last retrieved July 2007.

[17]   David C. Jenn, Rodney Johnson, Michael Melich, and Robert Broadston, "Wirelessly networked aperstructure digital phased array," Program Review, Naval Postgraduate School, May 2007 (unpublished).

[18]   McGrawHill/Osborne, *CWNA Certified Wireless Network Administrator*, third edition, pp. 303-319, McGraw-Hill, California, 2005.

[19]   Michael Steer, "Beyond 3G," IEEE Microwave Magazine, February 2007.

[20]   Steven J. Vaughan-Nichols, "Will the new Wi-Fi fly?" Technical Report No. 01707628, IEEE Computer Society, October 2006.

[21]   Rafael Kolic, "Ultra Wideband – the Next-Generation Wireless Connection," Technical Report, Device Forge, February 2004.

[22]   Tweak Town, "Intel demonstrates fast new Ultrawideband WPAN at IDF Taiwan," http://www.tweaktown.com/articles/968/intel_demonstrates_fast_new_ultrawideband_wpan_at_idf_taiwan/index.html, last retrieved July 2007.

[23]   William Stallings, *Data and computer communications*, eighth edition, pp. 104-116, Pearson Prentice Hall, New Jersey, 2007.

[24]   P. Ransom, "Photonic Crystal Waveguide," Presented at ONR 331 signatures D&I meeting, May 2007.

[25] National Instruments, "CompactRIO Real-Time Embedded Controllers," Data Sheet, http://www.ni.com/pdf/products/us/6358_crio_rt_controllers.pdf, last retrieved July 2007.

[26] National Instruments, "CompactRIO Reconfigurable chassis," Data Sheet, http://www.ni.com/pdf/products/us/cat_crio_9103.pdf, last retrieved July 2007.

[27] National Instruments, "C Series Analog Output Modules," Data Sheet, http://www.ni.com/pdf/products/us/c_series_ao.pdf, last retrieved July 2007.

[28] National Instruments, "C Series Analog Input Modules," Data Sheet, http://www.ni.com/pdf/products/us/c_series_ai.pdf, last retrieved July 2007.

[29] D-Link, "11a/11g Dualband Wireless Access Point," Data Sheet, ftp://ftp10.dlink.com/pdfs/products/DWL-7100AP/DWL-7100AP_ds.pdf, last retrieved July 2007.

[30] 3Com, "3Com 11a/b/g Wireless LAN Workgroup Bridge," Data Sheet, http://www.3com.com/products/en_U.S./detail.jsp?tab=features&pathtype=purchase&sku=3CRWE675075, last retrieved July 2007.

[31] National Instruments, "LabVIEW 8 FPGA Module Training," Tutorial, http://zone.ni.com/devzone/cda/tut/p/id/3555#toc0, last retrieved July 2007.

[32] Analog Devices, "AD8346 0.8 GHz to 2.5 GHz Quadrature Modulator," Data Sheet, http://www.analog.com/UploadedFiles/Data_Sheets/240325465AD8346_a.pdf, last retrieved August 2007.

[33] Analog Devices, "AD8347 0.8 GHz to 2.7 GHz Direct Convertion Quadrature Demodulator," Data Sheet, http://www.analog.com/UploadedFiles/Data_Sheets/230407246AD8347_a.pdf, last retrieved August 2007.

[34] NTL World, "Latency issues," http://homepage.ntlworld.com/robin.d.h.walker/cmtips/latency.html, last retrieved August 2007.

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